PRE-PHASE A SYSTEM STUDY OF A COMMERCIAL-SCALE SPACE-BASED SOLAR POWER (SBSP) SYSTEM FOR TERRESTRIAL NEEDS

FR – FINAL REPORT OF THE PRE-STUDY

REPORT TO
EUROPEAN SPACE AGENCY (ESA)

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ABBREVIATIONS

CAPEX – Capital Expenditures
CL – Coherent Light
CMG – Control moment gyroscope
ConOps – Concept of Operation
DSR – Direct Sun Reflection
DTO – Direct to Orbit.
ELY - Electrolysis
FDIR – Fault detection, isolation, and recovery
GEO – Geostationary Orbit
GPS – Ground Power Station
HLV – Heavy Launcher Vehicle
ITAR – International Traffic in Arms Regulations
KPI – Key Performance Indicator
LCOE – Levelized Cost of Energy.
LCOH – Levelized Cost of Hydrogen.
LEO – Low Earth Orbit
LEO&Sf – LEO & Solar Foil
NASA – National Aeronautics and Space Administration
NPV – Net Present Value
OPEX – Operating Expenses
PEM – Proton exchange membrane
PEEK – Polyetheretherketone
PV – Photovoltaic
SBSP – Space-Based Solar Power
SFC – Solar Fuel Cell
SpaceCo – Company operating the DSR
SRS – Sun Reflector Station
TCO – total cost of ownership
WACC – Weighted Average Cost of Capital

EXECUTIVE SUMMARY

This pre-study involved stakeholder engagement who see the Solar Based Solar Power project promising to boost renewable energy production but expressed concerns about social acceptance and environmental impact. Use cases analysis explored DSR applications based on energy output, location, operation time, and final use and the electricity production on grid in Europe and hydrogen production outside Europe have been retained as preferred use cases. A list of requirements outlines critical functional, mission, environmental, operational, and physical criteria.

Based on the global concept of Space Based Solar Power infrastructure with the mindset to produce green energy in the fastest time to market and the most competitive cost, DSR is a constellation of direct reflectors redirecting the sun power on ground stations, that can then generate electricity on the grid or hydrogen off grid. The elaborated architecture is a train of 3,987 large mirrors of 1km of diameter at a SSO orbit 890km-98° of inclination with 6-18 local solar time, each illuminating a ground station when they have a minimum of 20° of elevation angle. The train is designed to provide 1000W/m2 after atmospheric attenuation (like the sun), leading the simultaneous number of mirrors illuminating a single station[1], and its length is designed to illuminate 2 hours in dawn and dusk. The mirrors sweep from one ground station to another, providing sun energy to ~30 ground stations on earth.

DSR offers to boost the production of green energy of any sun-based ground operator with the best balance low risks/high resilience/high value concept. It provides a high impact of energy production (~40 to 60% of additional production without additional CAPEX) for any sun-based ground operator, leading to offer a competitive LCOH for the next decades, either as a space backbone dedicated to ground operators as third parties, or as an integrated company including ground facilities to fit with the ESA requirements to produce 10MtH2/year.

DSR will benefit from the expected growth of the ground sun-based technologies all over the world: PV will have the most important CAGR until 2040+ and volume to reach the sustainable development plan; Green hydrogen also, especially for industry and heavy mobility applications. And any technology improvements in PV or green hydrogen production[2] could be leveraged during the deployment and exploitation period. The impact of DSR on PV plants mitigates their negative impacts and restore their competitiveness compared to other renewable energies. DSR has very limited environmental impact by nature, thanks to natural illumination that does not exceed the power provided by the sun.

Thanks to a design-to-simplicity approach based on replicable modules with low technologies, the architecture is fully flexible, resilient to any disturbance and easy to deploy. In addition, the DSR project will have large impacts to other applications thanks to the maturation of key technologies, on space and on earth.

[1] Each redirect no more than 15W/m2, so the risks of safety are almost null.

[2] Like Solar Fuel technologies, turquoise hydrogen, thermal station, …etc.

The global roadmap for deployment is based on six main workstreams with a full-scale deployment possible in 2043. The approach for a sub scale demonstrator will help to derisk some critical issues (like the risk collision management in LEO orbit) and keep the momentum of the project with key milestones until MVP[3] deployed at the end of 2030 at the latest.

[3] Illumination of 50W/m2 for 10' at dawn and dusk, for PV stations and cities near the polar circle

1. STAKEHOLDER REQUIREMENTS

1.1 METHODOLOGY

In order to identify the stakeholder requirements, 9 ESA interviews complemented by 2 interviews within the consortium members have been conducted. In addition, an online survey has been sent to energy experts allowing to collect opinions from players on the entire value chain (*Figure 1*).

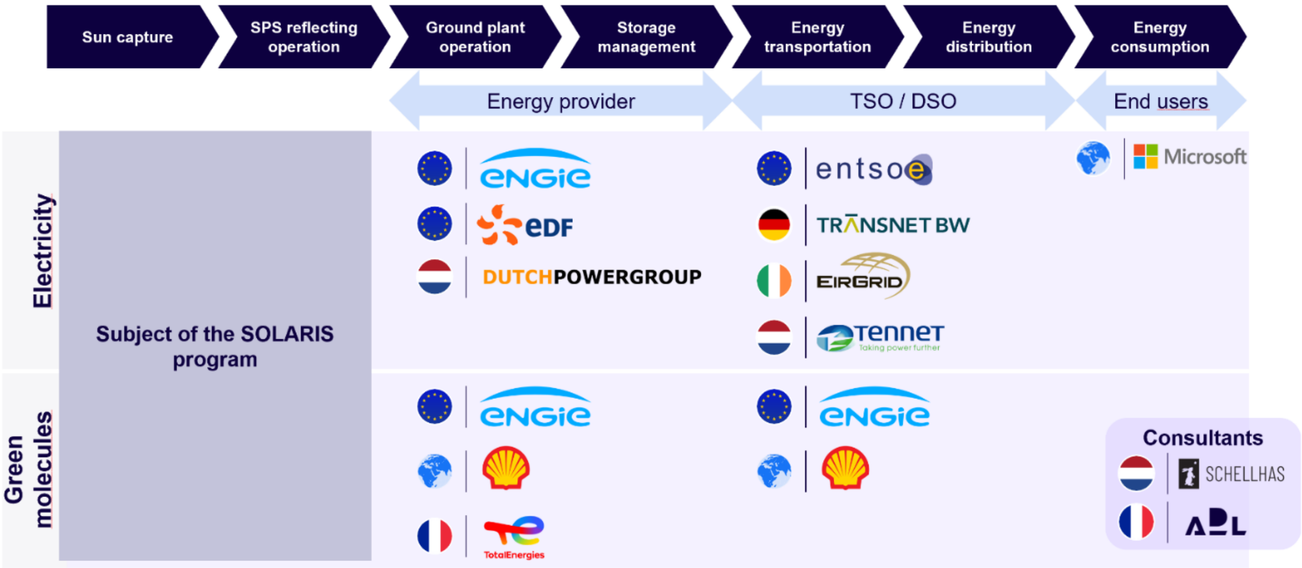


Figure 1 - Panel of the companies interviewed

Most of the interviewees consider the DSR concept promising because it could represent a source of renewable energy. However, they identify key issues in social acceptance and environmental damage (e.g. light pollution).

1.2 USE CASES

Various commercial use cases were proposed to interviewees depending on

- The energy output: electricity, green molecule, heat…
- The energy production site location: in or outside Europe
- The operation time: permanently, only during the day, only during the night…
- The final use: industrial, mobility, building…

Based on their answers, a SWOT analysis of the DSR concept has been performed, highlighting that output and location are the key dimensions of the use cases.

- **Strengths**

DSR can be used for several outputs: electricity, green molecules like H2, illumination for crops and could be deployed in the midterm (2030's). In addition, it could be mixed with offshore wind farms (floating PV) allowing a mutualization of permitting and connection CAPEX and an increase of capacity density and counter cycling production. DSR could also be used for Agri PV as light is the perfect solution for crops and it could provide extended light on earth whether in duration or in intensity.

- **Opportunities**

There is currently a structural under capacity to provide the low carbon needs for Europe, meaning that any solution will be considered, and a premium price is accepted for green. DSR could leverage existing PV farm park to increase their ROCE. In addition, the evolution of the regulation by countries will tend to favor new green capacities. DSR could also benefit from new technologies on ground like solar fuels to increase the yield performance or double it (e.g. Agri-PV). Finally, it could be deployed in equatorial countries that need to switch to green energy and have huge space.

- **Weaknesses**

Yet, DSR concept has a large spot size on ground that reduces largely the potential locations opportunities. Significant environmental impact must also be considered in case of full illumination or even less due to light pollution. DSR is also sensitive to sky coverage and provides therefore green energy still with intermittency.

- **Threats**

DSR will have to face ecologic lobbies that will fight to avoid any new locations and the strong power of the public acceptance that could ban night illumination. Geopolitics issues could jeopardize deployment outside Europe, especially near Equator. The economic added value of the SBSP compared to existing PV or offshore wind farms should also be demonstrated to convince stakeholders.

Different use cases have been identified based on the interest of each combination Output X Location to provide energy to Europe as final consumer and three main use cases seem offer the optimum in terms of Value-Fit (*Figure 2*). Offshore electricity (in Europe) and green hydrogen (Europe and outside) are clearly identified as most promising outputs, both in market-value and DSR-fit. Due to scarcity of space in Europe, electricity on land seems more difficult to achieve. Agri-PV was brought up as a potential solution. Desalination plants can be installed right next to hydrogen production, however value is less promising. Green e-fuels should be considered an option rather than a solution. In any case, hydrogen production is a prerequisite for e-fuel production.

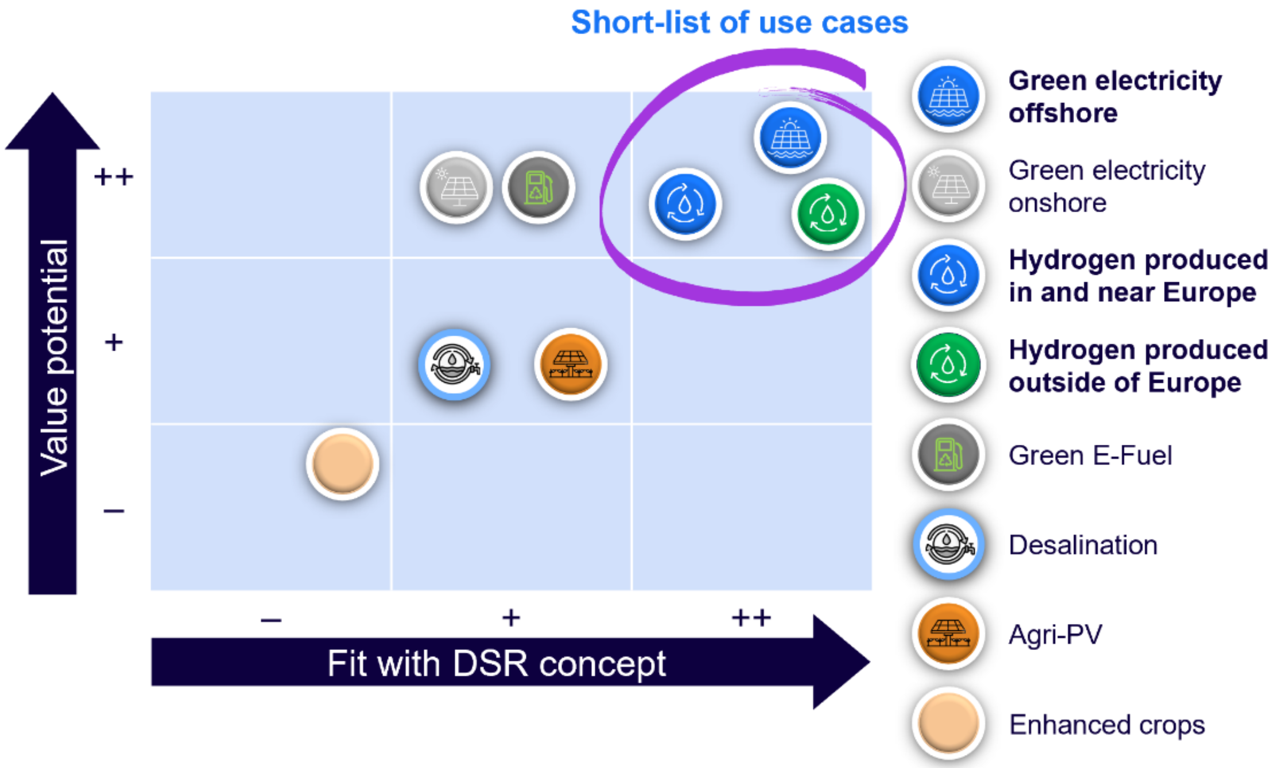


Figure 2 - Relative positions of outputs in terms of potential for DSR concept

Green electricity use-case

Electricity coming from DSR will be produced in Europe thanks to a PV farm in an isolated area or on offshore site coupled with offshore wind farm infrastructure, that could benefit from an increased capacity factor thanks to the different intermittent characteristics of the renewable energy sources. This solution could stabilize and facilitate the transport of electricity when the grid is congested, by switching from one PV plant to another. The DSR concept becomes interesting if it can timely start and stop and can direct the sunlight on multiple European sites in sequence.

Green molecule as hydrogen use-case

This use-case investigated how to produce green molecules (H2, CH4, CH3OH, NH3…) with the DSR concept, using the illumination to produce the molecules, either directly by the protons to generate the chemical reaction, or by generating electricity that will be used to activate the reaction.

Producing hydrogen and/or capturing carbon to convert them into other energy carriers is beneficial when electricity is present in excess and there is no grid connection. Hydrogen is costly to store and transport; transporting it from outside Europe in the form of other energy carriers (i.e. ammonia) eases the process, although it involves efficiency losses when converting it back in Europe. Green e-fuels should be considered an option rather than a solution.

In any case, hydrogen production is a prerequisite for e-fuel production. High-efficiency solar panels capable of directly converting sunlight into hydrogen are being developed (expected by 2030). Combined with DSR, this technology presents great potential for usage in southern Europe (i.e. Spain)

1.3 LIST OF REQUIREMENTS

This first phase of study allowed to identify the study objectives and requirements.

In the coming years, electricity and hydrogen demand will increase. The green electricity should be developed and improved to answer the rising demand accordingly to the transition energy requirements. The objectives of the study is to develop a flexible solution allowing the production of a large panel of green output whether electricity, green molecule as hydrogen, light or heat. It should also be abe to increase the current capacity production and to work with current ground installations and future plants. Finally, it should not present any safety concerns.

Based on these objectives, a list of requirements have been defined (*Table 1 - Requirement List*). Additional needs and goals are listed in DM1.

Criticality	Item	Source
	Functional requirements	
mandatory	The SBSP System shall direct the light beam or solar power in space to Ground power station on Earth	ESA
constraint	The nameplate capacity of each Ground Power Station with the SBSP System shall respect the grid and connection requirements due to it intermittency, with a maximum of 1 GW subject to each national electricity network constraints	Stakeholder
	Mission requirements	
mandatory	The SBSP System shall provide energy carrier power for commercial use in Europe or renewable power carriers for Europe	ESA
mandatory	The SBSP System shall not be designed to be easily used as arm for human on earth	Stakeholder
	Environmental requirements	
mandatory	The lifetime operations for the solar power satellite(s) in the SBSP system shall result in zero space debris.	ESA
mandatory	The system should be environmentally acceptable in all respects, including air pollution, water pollution, thermal pollution, hazards, land use, and any other unique factors associated with the particular nature of the system. The system, for example, must meet environmental standards (presently not well-defined) and public exposure to its light beam.	Stakeholder, ENGIE
	Operational requirements	
mandatory	Tje SBSP System shall be able to start / stop or redirect the light with a response time <15min (tbc)	Stakeholder
REQ	During a scheduled download session, the system availability is available shall be > 99% (tbc)	Stakeholder
	Physical requirements	
mandatory	The combined capability of all Space Solar Power Plants operating shall generate either up to 750 TWh (TBC) per year of operation by 2050 for electricity or 10% of the European hydrogen consumption forecast in 2050.	ESA

Table 1 - Requirement List

2. LITERATURE REVIEW

The use of orbiting mirrors to reflect sunlight to Earth for a multitude of interesting applications was originally described in 1929 by the German space pioneer Hermann Oberth in his book entitled "Ways to Spaceflight". These applications included the illumination of cities, melting of frozen waterways, and modifications to the weather and climate. Professor Oberth was not content with just proposing the idea; he also went into considerable detail to support it mathematically and to show how it could be implemented.

However, Oberth was so far ahead of his time that the technology was not available in 1929 to implement his advanced concepts. The next thorough treatment of orbiting solar reflectors was presented about 38 years later by A. G. Buckingham.

Buckingham's early efforts were primarily concerned with illumination from space for both civil and military applications. Much of the work was released in 1967 and 1968 in papers written by Buckingham and H. M. Watson. During this time period, solar reflectors were studied for use in the war in Vietnam by several companies. The technology existed for fabricating and launching the reflector sizes under consideration (approximately 75 m in diameter), but even with the advocacy of NASA and the Air Force the project was cancelled, primarily because of an anticipated early end of the war.

A more comprehensive treatment of orbiting solar reflectors, their missions, and applications has been by Krafft A. Ehricke, a renowned engineer responsible for many of this country's space age developments. Dr. Ehricke published papers on "space light" from 1970. His studies cover the broad spectrum of potential applications including illumination, increased plant yield by enhancing photosynthesis, electric power generation, and climate control.

The most intensive studies of solar reflectors for the production of electrical energy were conducted by Kenneth W. Billman and associates at the NASA Ames Research genter from 1976 to 1979, in a study program designated SOLARES. The results of these studies indicated that the SOLARES baseline concept, which used 80 000 of 1-km orbiting reflectors that could generate 220 GW of electricity. These studies were terminated in 1979 at the Ames Research Center. The NASA Langley Research Center took over from 1977 to 1981 to better define solar-reflector applications pertinent mainly to energy production and illumination from space. A 1982 NASA Technical Paper which gathers a synthesis of physical equations to be taken into account was issued in 1982 to presents the findings of these studies, of but it is limited to only those concerning illumination from space. Its table of content is provided in annex in order to show the covered topics

Along with deployment of photovoltaic solar farms from the late 2000s, other studies of orbiting solar reflectors have focused on applications for terrestrial solar power enhancement. Some envisaged a constellation of 18 reflectors (each comprising a 10 km diameter array of individual 1 km reflectors) in a 1000 km polar orbit servicing some 40 solar power plants during dawn and dusk.

In parallel, the concept of energy transport by radiofrequency beam is patented by Peter Glaser in 1973 and matures up to today.

However, none of these previous DSR studies materialize in projects explained by physics or geopolitical reasons.

- **The minimal size of illuminated spot on the ground**

The sun generates a very large spot-on ground from a flat mirror placed thousands of kilometers away. It was not a concern, a century ago, when foreseen applications were illumination of cities or heating of frozen area. But power delivery cannot come with cancellation of the night for millions of citizens around.

- **The complexity of huge assembly in space**

Assembly of a monolithic flat mirror of several km2 is out of current state of art. In addition, it is very complex to manage its attitude in front of all the applied forces (solar pressure, space weather, gyroscopic torques, inertia, drag, gravity gradient …). It is very challenging to repoint it constantly with accuracy. It is very challenging to shape accurately its flatness or concavity. Such a huge assembly is fragile in front of debris collision, is not easy to maintain, to repair or to upgrade.

- **The low competitiveness of photovoltaic solar energy before 2010's**

During decades, the PV solar energy was convenient only for small applications in remote area, far from electric grid, but was not competitive for large power plants. It is with the pressure of the global warming, thanks also to technological improvement, that solar farms started to take place in the energy mix, connected to the grid altogether with other renewable energy. Today hundreds of billion dollars are invested in solar farms around the world.

- **The quest for local energy supplies**

Because space can deliver everywhere on Earth, the natural aim for space-based solar power is to deliver directly next to the end user, just like all the other space applications. Because direct sun reflection power cannot be delivered without light, it cannot feed the local need in electricity of end-users in inhabited area, like European citizen. But electricity is only 20% of European energy consumption. Meanwhile, the European citizens are locally fed, at 80%, by fossil energy which is imported (and which is generating CO_2 in European air, wherever the fossil energy comes from).

3. ARCHITECTURE PRE-SELECTION

Considering the global architecture design, it is important to consider three types of trades:

- The system requirements, especially the ones that are not mandatory but valuable
- The trades associated to the ground segment
- The trades associated to the space segment

3.1 REQUIREMENTS AND NEEDS

Although all the requirements will impact the architecture to some extent, three of them will have the most impact for the design of the DSR concept:

- The total energy produced by the SBSP system should be 750 TWh in 2050
- The spot size should be minimized for light pollution when ground segment is located in inhabited area
- The minimum power density to activate the cells should higher than 200W/m^2

3.2 TRADES FOR GROUND SEGMENT

Five main trades have been identified for the ground segment: the final output, the GPS location, the power range, the illumination period and type of panels. There are summarized in the table below (*Table 2*).

Trade	Description	Potential values	Remarks
Final Output	As described in the TN1 document, major use cases are based on the outputs generated by the system. Two most promising outputs have been pre-selected. This output could vary upon the location of the plant	Electricity direct to the grid	ESA preferred output, even if electricity represents ~20% of the energy consumed by Europe
		Solar molecules	Mostly H2, but potentially others derivatives like Ammonia, Methane…
Location of the GPS plant	The location should take into account the spot size generated by the SPS, due to light pollution and environmental impact. The location impacts also the cloud coverage and the variation of the day duration (quite	Onshore Europe	ESA preferred option but it is more and more difficult to find new location. The spot size is the biggest drawbacks for a full deployment in this option
		Offshore Europe	Can be interesting as there could be some available locations to deploy DSR farms with a quite large spot size (especially combined with offshore wind).
		Outside Europe	As this level, we do not split into several areas but only consider areas where any spot size can be accepted. Some areas offer very favorable load factor (dry weather)

	stable near equator)		
Power range / GPS	Due to technical constraints, the minimum power of the plant has to respect some limits, mainly by output	Less than 1GW	Easier connection to the grid to avoid too much regulation perturbance
		From 1 to 5GW	Could be used for electricity combined with large storage capacity in order to inject in the grid only the needed energy
		More than 5GW	Seems to be the minimum for producing solar molecules and H_2 with the critical size (please note that the Graveline nuclear plant power is about 5GW)
Illumination period	The period of the day where the SPS send energy is key for the sizing case	Only dawn and dusk	Typically 2h in the morning and before night
		Extended day	From 7am to 9pm (increase the energy received during the whole working day time)
		24/7	Most interesting to maximize the ROCE of the infrastructure but not possible near population. Could have an environmental impact
Type of panels	The technology to convert the sun energy onto the final output	Photovoltaic panel	Classic technology to generate electricity
		Photovoltaic panel combined with electrolysis	Current technology to generate H2 from sun – Low yield rate
		Solar fuel panel	New emerging technology to generate H2 with a direct reaction
		Adapted wavelength panel	Emerging technology to design panels that maximize the yield for the laser wavelength (1064nm)

Table 2 - Trades for ground segment

3.3 TRADES FOR SPACE SEGMENT

The table below identifies a first list of what could be the trades to consider for selecting the best architecture and the range of values for each (*Table 3*).

Trade	Description	Potential values	Remarks
Orbit distance	The orbit will determine the spot size and the move between the GPS and the SPS if it is not GEO	GEO	Simplest orbit as the SPS is fixed for the GPS on earth. Single satellite system may suffices.
		SSO 6-18LST (1400km)	Lowest orbit without eclipse but orbital plane near the dawn and dusk. Constellation is required.
		890km	Ideally to minimize the spot size. Constellation is required.
		Other	Other elliptical orbit non considered as more interesting than SSO wrt illumination
Orbit inclination	The inclination determine the earth area covered by the SPS	~0° (Equatorial and south of Europe)	Allow to target ground segment near equator by keeping illumination at the zenith
		I°	Optimal orbit to cover the targeted areas of the plants (inclination imposed by SSO orbit definition)
		90°	To target polar and north of Europe where offshore winds offer available areas to accept large solar farms
Payload technology	The form factor the SPS will be key to determine the overall performance of the system	Multi Small	Typically, a group of small satellites with mirror up to 100 m of diameter, pointed to target a single point at earth
		Multi Large	Typically, a group of satellites with mirror of 1000 m of diameter, pointed to target a single point at earth
		Single Large Flat	A single satellite targeting one GPS with a flat mirror of several km^2 (state of the art of the

			DSR technology) to generate enough energy to activate cells
		Single Large Shaped (parabolic)	In this case, the mirror is shaped to focuse the light and reduce the spot size on earth
		Solar coherent light	System allowing to generate a laser beam from solar flux, without electric conversion, after concentrating the Sun light received. The light beam has a very narrow size providing a high power density spot size.

Table 3 - Trades for space segment

Architecture pruning

Based on a scenario analysis assessing the value of payload technology for mirrors according to the orbit, two main architectures present some promising results: Direct Sun Reflection and Coherent Light (*Table 4*). Details on each architecture are provided in TN3.

Parameter	Architecture DSR	Architecture Solar Coherent Light
Orbit altitude	890 km (LEO)	36 000km (GEO)
Orbit inclination	I°	0°
Payload technology	Direct Sun Reflecting with Multi Large mirrors	Solar Coherent Light
Final Output	Solar Molecules and / or PV in Europe (tbd)	Electricity mainly but could be deployed for solar molecules
Location of the GPS plant	Near the equator in desert or off shore Europe + outside Europe	Mainly Europe but possible elsewhere
Power range / GPS	>5GW ideally and no more than 1GW on-grid	< 1GW ideally for electricity
Illumination period	Extended day (depending the LCOE and the environmental impact)	24/7

Table 4 - Key elements of pre-selected architectures

Analysis demonstrated that the SCL is the most promising technology in terms of efficacy: it enables for less infrastructure, smaller beams and less environmental impact (ground and visible footprint). However, its system complexity is higher and there is a safety concern if light ray is deviated since it is very concentrated and irradiance can be up to 2,000W/m^2.

Therefore, the reference space architecture selected is the Direct Sun Reflection concept that will be further developed in next sections.

4. REFERENCE ARCHITECTURE DEFINITION

SECTION KEY MESSAGES

- The reference DSR architecture is a train of SRS in LEO orbit illuminating a group of existing or new GPS, providing a power of 1,000W/m2 on each during essentially four hours (two hours at dawn and two hours at dusk).
- In the DSR concept, each single SRS will illuminate with an irradiance depending on its elevation.

4.1 DSR CONCEPT KEY PRINCIPLES

The proposed DSR architecture is composed of a train of SRS in LEO orbit, which illuminates a group of existing or new PV plants *(Figure 1).* The train of SRS is designed to provide a power of 1,000 W/m^2 on each single GPS over which it flies and to illuminate an equatorial GPS for four hours (two hours at dawn and two hours at dusk) or non-equatorial GPS for three hours (2 hours at dawn or dusk + an additional one hour).

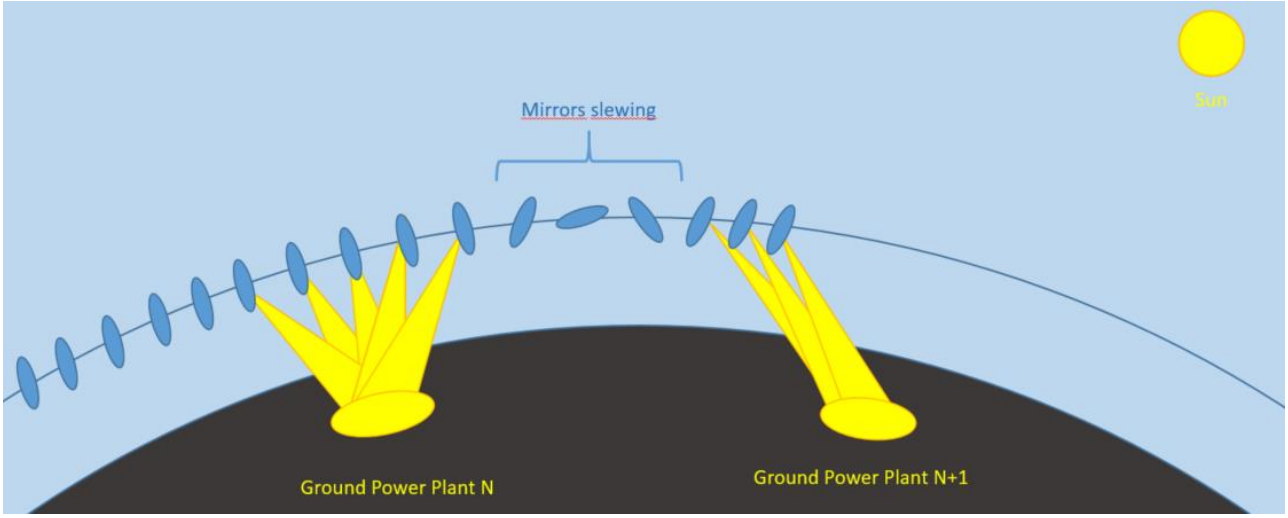


Figure 3 - DSR concept

Each single SRS will illuminate with an irradiance depending on its elevation *(Figure 2).* The power sent by an SRS increases with its elevation: 1W/m2 at 30° then 5W/m2 at 55° to reach its peak of 10W/m2 at 90° and then decrease. No illumination is sent to ground when the SRS is lower than 20°. Because a single SRS can provide at its peak elevation of 90° a maximum power of 10W/m^2, there is no major safety concern if its light ray is deviated.

To maintain an illumination of 1,000W/m^2 on each GPS, a defined number of mirrors required within the visibility window will be determined and each time a SRS leaves the window, a new one enters it.

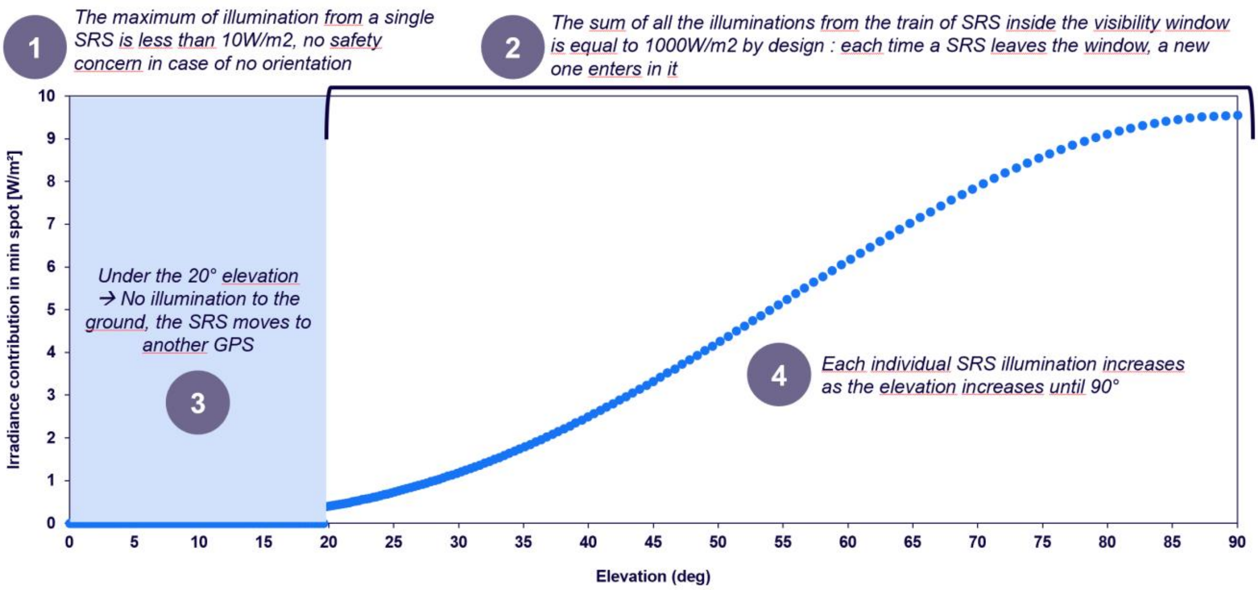


Figure 4 - Power sent by a single SRS on a GPS depending on its elevation.

From the power received by SRS, the GPS will generate electricity to be used in Europe when connected to the grid and hydrogen when the plant is located outside Europe or exceeds the limit of grid connection (production > 1 GW).

4.2 DSR CONCEPT BENEFITS & CONCERNS

Three major benefits of the DSR concept have been identified:

- The train of SRS will illuminate up to 1,000W/m^2 which is equivalent to the power provided on the ground by the sun, as explained above
- The deployment of the architecture is flexible and modular, based on a constellation of SRS that can be upgraded along the deployment period and is therefore resilient to any perturbance
- Most of the technology proposed are mature (reflecting mirror, lightweight structure, photovoltaic panels, electrolysis) or in advanced development (solar fuel cell) and existing PV stations will be leveraged.

Yet, two majors' concerns cloud the concept.

- The minimum spot size area of each SRS on the ground is 8.3km^2 at 90° and will increase in elliptical form when it is lower than peak elevation, leading to carefully selecting the location of the GPS
- The PV to electricity efficiency rate is weak reaching only 27% for a PV plant

5. DEFINITION OF THE SPACE SEGMENT

SECTION KEY MESSAGES

- KPIs of the DSR constellation clearly show the massive size of the infrastructure
- Direct Sun Reflection (DSR) is considered at 890km-orbit to optimize drag force, spot size on Earth and possibility to illuminate an area twice a day.
- The volume and design of a single SRS is estimated based on a NASA study from 1980's.
- A major point of solar reflector performance is the flatness of the reflecting membrane and the global mass, leading to a circular design already studied by NASA.
- The main part of the structure is composed of truss structure (external ring & central masts) deployed into orbit; after deep studies, collapsible truss structure is preferred.
- The reflecting membrane will be a double-sided aluminized thin film of PEEK due to its tear resistance, lower density (mass), lower cost and is ITAR free.
- Solar sailing will be used for orbital control, leveraging the design of the SRS.
- The attitude control, compliant with the angular acceleration needed for tracking GPS in this orbit, needs to design essentially very two large CMGs and a specific innovative system.
- Dealing with a flexible platform while keeping an accurate pointing necessitates to employ an accurate positional reference system.
- The communication and data handling module are very simple and based on generic solution, due to our passive concept on space.
- Power will be generated by PV panels located in the top and bottom of the mast.
- The bottom-up mass per SRS is estimated to 11,4 tons
- SRS total construction accounts for a negligible part of the space-segment carbon footprint

The architecture to be deployed in space for the DSR project is massive, in terms of number of units, size or mass. The constellation will be composed of 3,987 SRS, representing a total mass of 45,404 tons and 103,000 single units. The train will be spread on 57,000km-long and the global surface deployed will approximately reach 3,131km^2.

The selected orbit is a 6-18 Local Solar Time (LST) Sun Synchronous Orbit at an altitude of 890 km. Indeed, the lower the altitude is, the smaller the light spot-on ground is and then the necessary number of mirrors to get enough illumination is. It is also beneficial because it minimizes the size of the ground solar installation surface and then reduces the footprint. Moreover, at this specific altitude, the orbital period is a multiple of 12 hours. The consequence is that each reflector could flyby the same ground site twice a day, respectively at 6h and 18h LST. This is particularly interesting to maximize the use of the same ground sites. However, night condition depends on seasonal effects unless for geographic locations of latitudes between -20°/+20°. In our case, the most interesting local solar time is 6h – 18h, meaning that the reflectors will fly by the same region at sunset and sunrise.

On the other hand, a lower orbit brings important shortcomings. First, the increase of drag. Even though still at "high" LEO orbit, given the large and lightweight platform, the effect of the drag is not negligible anymore and would represent an important orbit decay if not compensated by orbit raising maneuvers.

Other important variables for the orbit, attitude control et structure used to design the space architecture have been summarized in the *Table 5* below.

Domain	Parameter	Refercen Value
Orbit	Altitude	890 km
	Inclination	98.98 deg
	Orbit type	Sun-Synchronous 6-18 Local Solar Time, with repeating ground track
	Passes / cycle	14 orbits per 24h cycle
	Serviceable GPS	Up to 10 per orbit (every 4000 km)
	Number of reflectors	3 987 – 257 in visibility (above 20° of elevation angle)
Attitude control	Main actuator	2 x Control Momentum Gyros on the central mast, on each side of the membrane
	Rotor angular momentum	5 105 000 Nms
	Peak torque (total)	47 000 Nm
	Rotor radius	10 m
	Rotor angular velocity	157 rad/s (1 500 tr/min)
	Rotor material	Carbon fiber - Resin
	Total actuators mass	CMGs 3 300 kg + Mobile mass 1 000 kg
Structure	Type	Collapsed deployable triangular sections trusses of 1 m long
	Number of triangle sections for the ring	3600: 90 units of collapsed triangular sections of 34 m long
	Total single reflector mass (with actuators)	11 365 kg (Total mass = 62,6kt)
	Size	1 km circle with central mast
	Areal density	14.5 g/m²
	Material	Carbon fiber - Resin for structure, KEEP for membrane

Table 5 - Design variables for space

Four elements are key in a SRS: the platform including the structure and reflecting surface, the AOCS for the orbit and attitude control, communication and data handling and the power.

5.1 THE PLATFORM

The DSR elements shall be, as much as possible conceived to be disassembled and manipulated by a robotic arm for maintenance and end of life dismantling purpose.

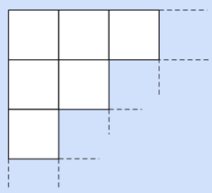
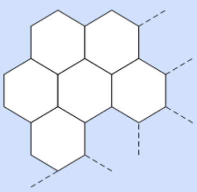
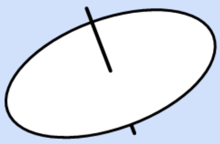
5.1.1 THE STRUCTURE

A major point of SRS performance is the flatness of the reflecting membrane. To ensure this flatness, the membrane must be sufficiently taut, and the structure must maintain its geometry.

To ensure the reflecting membrane tension, a "spring" system must be installed all around the membrane to ensure force distribution (avoid having too large local forces) and avoid folds on the membrane. These tension systems must compensate a thermal expansion of the membrane. The implementation of a membrane tension system has a mechanical impact on the structure into mass and directs the chosen solutions.

To maintain its geometry, the structure must have the greatest possible stiffness. On an object like the plan solar reflector (2 dimensions), it's difficult. To gain stiffness, the structure will have to distribute the forces outside reflector plane. This will impact mass and implementation.

The objective of this study (given the size of the object) is to make a reflector and a structure as light as possible. The inertias for the AOCS must be as low as possible. The reflector choice with the lower thickness and the lower density is necessary. This material must be the most reflective and must be able to unfold in space to take up as little space as possible upon launch. The choice of solid mirror was therefore excluded from the start of this study
For the overall architecture, three solutions were considered with the advantages and disadvantages detailed in the following table:

Solution	Advantage	Disadvantage
Square solution 	• Easier solution to achieve individuall • Ease of deploying the reflective surface (rectangular strips) • Allows to create a small-scale demonstrator	• Lots of structural assembly • High mass • Many elements to constitute the objective surface area of 785,000m² (area of 1km of diameter circle)
Hexagonal solution 	• Easy solution to make individually • Allows you to create a small-scale demonstrator	• Reflective surface in the form of a triangular element (deployment more difficult) • Lots of structural assembly • High mass • Lots of subassembly to constitute the objective surface area of 785,000m² (area of 1km of diameter circle)
Circular solution 	• Less structure to constitute the objective surface area of 785,000m² – Lower overall mass – Reduced overall inertia	• Deployment in space (Single launch solution with global deployment or assembly in orbit with multi launch) • Deployment of the reflective surface more difficult due to the surface

Selected design

Table 6 - Comparison between 3 platform designs

The solution chosen for the study was the circular one with central mast and shrouds, which has already been studied by NASA in the 1980's. The objective being to move towards a solution with the least structural element to achieve the objective surface area of 785,000m². The selected structure is further detailed in the TN4. The completely packaged baseline design occupies a nearly cylindrical volume with a 4.3-m-maximum diameter and a 15-m maximum length, resulting in an estimated volume of 217m^3. The SRS deployment process is organized in 3 steps *(Figure 5)*: the launching of SRS to the parking orbit, the deployment of canisters and finally the deployment of the 3 wheels one by one.

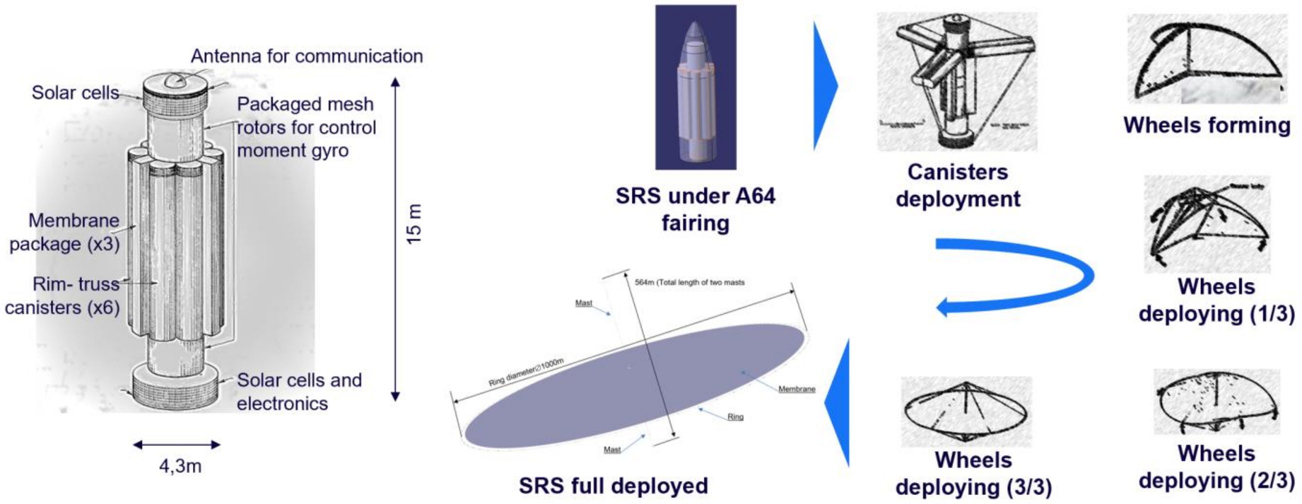
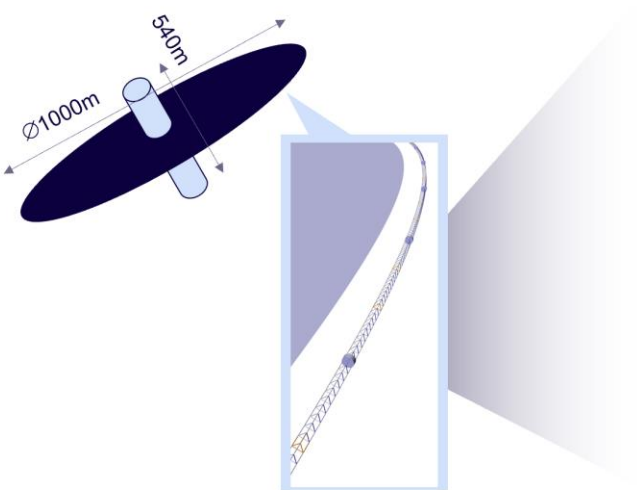


Figure 5 - Folded SRS design by NASA study (left) and its deployment process (right)

The ring is made up of 90 compartments including 30 elementary trusses. The following three views show a deployed compartment, the stored compartment and the dimensions of an elementary trusses used for ring. Each mast is made up of 6 compartments including 30 elementary trusses. The following three views show a deployed compartment, the stored compartment and the dimensions of an elementary trusses used for ring. 90 film expansion compensators are fixed on the trusses compartment of the ring and serve to tension the membrane and compensate for its thermal expansion.

The main part of the structure is composed of truss structure (external ring & central masts) deployed into orbit; after deep studies, collapsible truss structure is preferred for its common use better resistance to compression and easiness to fabricate (*Figure 6*).



	Collapsible	Coilable
Advantage	• Used extensively in other designs of similar systems • Easy to understand, analyze, and fabricate • One class of moving part, a spring loaded hinge • Better resistance to compression of the coilable truss structure solution	• Flexibility in design choice for the small connectors and stowage configuration • No motor needed • Very strong flight heritage and resources are available for design reference
Dis-advantage	• Mass higher • Stored dimension higher than the coilable truss structure solution • With a lot of pieces, there is a higher chance for individual part failure	• Stowage of the diagonals may be difficult to accurately predict with each redeployment • Very low resistance to compression
	Selected design	

Figure 6 - Structure design (left) and types of truss structure analyzed (right)

5.1.2 THE REFLECTIVE MEMBRANE

Two materials were selected to produce the reflective membrane. PEEK or KAPTON. Both used by Thales for satellite isolation and having a strong heritage and flight. Information on these materials is presented in the *Table 7*.

	Unit	PEEK			Kapton		
Material		PEEK™ AptivTM polymer films			Kapton		
Manufacturer		VICTREX®			DUPONT / MICEL		
Thickness	µm	4 (hypothesis)	8	25	4 (hypothesis)	7,5	25
Development maturity	TRL	**Not yet produced**[1]	9	9	Not yet produced	9	9
Density	kg/m3	1,3			1.42		
Mass	g/m²		10.4	32.5		10.6	35.5
Coefficient of Linear Thermal Expansion	ppm/°C	47			46		
Fracture strain	%	>150			72		
Moisture absorption 23°C, 24h, 50%RH	%	0,04			18		
Cost	k€/kg		0.42	0.26		1.3	0.55
Qualification temperature	°C	-180 / +250			-180 / +250		

Selected design

Table 7 - Comparison between PEEK and Kapton

Two types of leaves were analyzed: aluminum 1 or 2 sides. The resulting temperatures are compliant to qualification of materials (*Table 8*). The maximum expansion relative to 20°C of 2 sides aluminized PEEK is -0.6m when the reflector is at +8°C in eclipse and +7.5m when the reflector is at 183°C in fully sunshine. Maximal 10m is a good value to be considered for the next studies and this value will be taken into account for the design of the tensioner and the structure.

Membrane temperature	Aluminum one side	Aluminum two sides
Nominal mode	-26°C	+173
Fully sunshine (sun normal to reflector	+3°C	+183°C
Eclipse	-103°C	+8°C

Table 8 - Temperatures compliant for qualification of material with two sides

The two products are compatible, the choice will be made according to the mass and discussions with the manufacturers for thinner thicknesses. But the baseline for this study will be PEEK because it has better tear resistance, lower density (mass) and is ITAR free. The cost of PEEK material is around a half of Kapton.

5.2 AOCS

5.2.1 ORBITAL CONTROL

Orbital control is needed for:

- Orbit raising from the parking orbit where the reflector was assembled up to the final orbit location,
- Orbital station keeping, essentially because of the remaining drag force at 890 km,
- Collision avoidance maneuvers

The yearly cost to compensate the altitude decay with control jets is huge, even with very efficient electrical propulsion: about 540 kg of Xenon for a single reflector. If multiplied by the number of reflectors composing the constellation, it leads to an unrealistic amount of fuel to be brought in space yearly. A smarter and more viable solution is to take advantage of the extremely large and lightweight surface of the reflector to use it as a solar sail for orbital control. This is also what is proposed in [NASA][4] and [Solspace][5] studies.

Then solar sailing is adequate for orbit raising as long as launcher injection is above 680 km. Nevertheless, it still has to be estimated if with such a method the control authority allows to perform station keeping maneuvers while solar sail attitude is constrained by direct solar reflection towards ground stations, and also if it is compatible with orbit insertion in the constellation. For this latter case, a solution could be to insert new reflectors at the head or at the tail of the constellation train. Moreover, if deemed necessary, space tugs could participate to special orbital control maneuvers.

5.2.2 ATTITUDE CONTROL

Main actuator

Due to the orbit choice and the minimum inter-GPS distance, specific angular accelerations will have to be applied to the platform *(Table 9*). Among these two, the inter-GPS acceleration with double sided reflecting membrane is the most demanding with 9.63E-5 rad/s². This is the value to be considered for the attitude control sizing.

[4] *John M. Hedgepeth et al, Conceptual Design Studies for Large free-flying Solar Reflector Spacecraft, 1981*

[5] *Andrea Viale et al, A reference architecture for orbiting solar reflectors to enhance terrestrial solar power plant output, 2023*

Constraint origin	Max angular acceleration [rad/s²]	Max angular rate [rad/s]
GPS tracking	2,32E-05	6,44E-03
Inter-GPS repointing	**9,63E-05**	1,23E-02

Sizing value

Table 9 - Angular rate and accelerations to manage

Since the inertia about the platform diameter is 4,91E+08 kg.m², the necessary torque to be applied to reach this angular acceleration is 47 262 N.m, which is huge with respect to the largest existing CMG in space, which are used in the ISS and can provide a torque of 258 Nm. For a preliminary sizing, one can consider that the torque T of the CMG is proportional to product of the angular momentum of the wheels H_w with the gimbals angular velocities $\dot{\theta}$: $H_w \times \dot{\theta} \cong T$
Where $H_w = I \times \omega_w$ where the inertia about the diameter is $I = 1/2\ mr^2$ if we approximate the CMG flywheel rotor as a thin rotating ring of a mass m and a radius r.

The main driver of the torque of the CMG is the radius of its flywheel as it weights to the square with respect to other parameters of the above equation. This is why it is highly preferable to favor very large but lightweight flywheels.

Then, to reach the needed torque for maneuvering, the sizing led to two two-axis CMGs mounted one on each side of the central part of the mast, one on each side of the mirror membrane. Flywheels axis are aligned with the central mast axis. But since these flywheels have to be extremely large, their sizing have to limit the tilting angle.

Each flywheel has a diameter of 20 m, a mass of 650 kg, providing an inertia of 32 500 kg.m², spinning at 1500 roll per minute. These flywheels actuated by gimbals are able to tilt them at an angular rate of 4.6E-3 rad/s which is low in order to limit the needed tilt angle one and also to prevent from gimbal lock effect.

In order to resist to the important centrifugal acceleration of 246 740 m/s², the flywheel could be a rigid rod of carbon-resin with a density of 1600 kg/m3, and if so it would have a cylindrical section of 9 cm. Of course, elements (bows and radiuses) of these two 20 m diameter flywheels should be assembled and/or deployed once in orbit in order to fit into the launcher's fairing. With such an attitude control system, there is no control about the reflector axis with the CMG. This is correct if we only consider the gimbals action, but changing the flywheels rotation speeds provide an additional (third) degree of freedom about the reflector axis which is anyway not meant to be solicited.

At first order, it was estimated that the average power consumption needed for the attitude control with two CMGs is about 200 W with peak power need estimated to about 600W to reach the max inter-GPS torque of 47 kN.m.

Pointing accuracy

The need is to avoid beam excursions beyond about 2.5% of the spot size, which represents approximately 225 m. This implies a pointing accuracy of 0.25 mrad to be performed.

To do so, two actuators are involved:

1. The platform attitude control itself, relying on CMGs,
2. The mirror shape, thanks to tendons connected to the membrane, ensuring a dynamic shaping of the membrane

In order to feed the closed loop controller, it is proposed to use the sensing method inspired by large antennas pointing. The RF sensing method consists in a combination of RF measurements via the RF sensing system. RF measurements are performed through quartets of dedicated beams placed on the platform, centered on a number of fixed ground beacons. The pointing errors are derived from on-ground processing of those measurements, and a corrected set of actuators commands is regularly computed and uploaded to the satellite to compensate the errors.

Oscillation management

Even if for this preliminary AOCS sizing the large platform was considered as rigid, it should in reality be considered as flexible, with main modes estimation range from 0.025 to 0.25 Hz according to NASA. A detailed and updated estimation has been done by module:

- Membrane: main mode is 0.019 Hz
- Structure: main mode is 0.03 Hz
- Mast: main mode is 0.17 Hz

It is important to highlight that several solutions could be combined to deal with this low natural frequency to make possible attitude control of this large structure, particularly to reach the pointing performance.

First, since the lowest frequency comes from the membrane, two solutions can be considered:

1. To make the membrane lighter by selecting a 2 µm thin membrane. Even if such a thickness seems reachable today, the counterpart is that it is less resistant to tears and space debris/meteoroids impacts.
2. To damp the membrane oscillations with lines connecting the membrane to spokes. Indeed, the simple fact to add these connections increases noticeably the frequency of the membrane’s natural modes. In addition, use of dampers and springs along these lines could then deal with the residual oscillations.

The second is preferred since it saves mass and is very efficient. Indeed, if used in as illustrated below (*Figure 7*), it would shift the natural frequency from 0.019 up to 0.18 Hz.

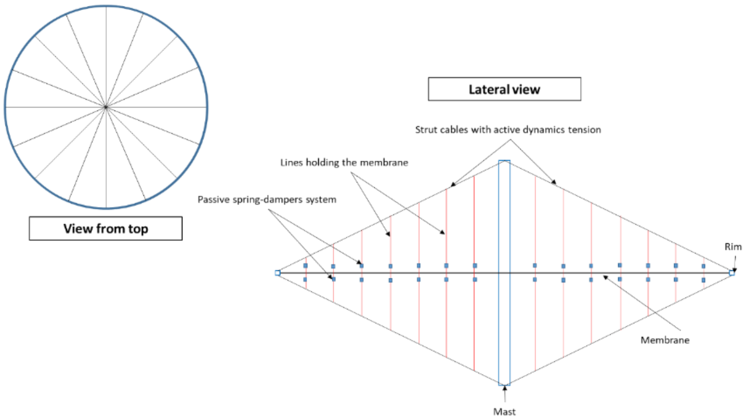


Figure 7 - Platform solutions to deal with membrane low natural frequency

In complement to the previous solution, an active control of the spokes cables tension to dampen the oscillations of the structure can be used to compensate membrane and structure oscillations.
Finally, a smart attitude control law could be elaborated able to deal with pointing performance while preventing from natural modes excitation. It would be a very complex control law given the number of sensors (strain gauges, optical/laser metrology, …) and actuators (passive: dampers, active: CMGs and screw jacks for the lines) involved in the loop but this complexity can be managed with nowadays simulation tools and IA engines.

5.3 COMMUNICATION & DATA HANDLING

5.3.1 COMMUNICATION

The communication between ground and reflector is limited to housekeeping telemetry to report the reflector status, and AOCS parameters. If need be, some sensors data could be downloaded for monitoring or investigations. Evenly, limited telecommands should be sent by the ground control center, essentially to plan attitude and maneuver plans.

Consequently, given the low altitude orbit, a simple S-band communication subsystem with a few kbps of TMTC and two omnidirectional small antennas (less than 1 kg each) should be sufficient to cover the mission's needs. In addition, this equipment is very resistant to the space environment (some of them were used on Rosetta mission) and transceiver only require about 5 W to work, for a mass of about 5 kg.

5.3.2 DATA HANDLING

The computational need is very limited for reflectors normal work, as it essentially loads and propagate orbits and applies the maneuvering plan. However, in some critical situations like after a collision with a debris, the reflector should be able to manage safety attitude or orbital maneuvers autonomously and to do so to be able to elaborate quickly a status of the situation by processing information from several sensors. Moreover the constraints of reliability and life expectancy in space environment are of course also critical. This is why we can consider to use data handling subsystem similar to existing ones for small generic platforms, including their on-board computers with an additional redundancy and hardening to comply with the mission. Then a power consumption of 30 W and a mass of 10 kg can be considered. Two units are required for redundancy purpose but only one is used at a time.

A set of AOCS sensors are needed. It is composed of two sets (for redundancy) of: 3 star trackers, 2 Inertial Measurement Units (IMU). Each set mass is estimated to 10 kg. The pointing accuracy could also be ensured by a closed loop with ground sensors feeding the control loop through communication subsystem.

A set of monitoring sensors like cameras, strain and temperature gauges, are also dispatched on the structure. These are low consumption sensors, using Internet of the Things technologies. It is assumed they represent a mass of 30 kg and a power consumption of 30 W.

5.4 POWER

The power subsystem is in charge of power generation, storage and dispatching in order to feed the electrical equipment of the reflector of which the average consumption is estimated to 283 W. To do so, the power subsystem is composed of *(Table 10)*:

- Solar generators accommodated on the tips cylinders of the upper and lower masts in order to see the Sunlight when tracking or repointing the GPS. A total surface of 70 m² was estimated to wrap these cylinders, leading to a mass of 255 kg.
- Batteries, to store energy of exceeding power collected from Sun during daylight and providing power while in eclipse. A total mass of 15 kg of batteries (typically composed of SAFT Li-ion VES16 elements) was provisioned to cover the energy storage need of 30 years.
- Power management: necessary elements to transform and supply power to the demanding elements. These elements overall mass is estimated to 30 kg (they are doubled for redundancy).

Subsystem	Item	Quantity	Power consumption [W]
AOCS	CMG	2	108
Communication	Transceiver	1	5
Data handling	Computer	1	30
	Set of sensors (3 STR, 2 IMU)	1	10
	Set of monitoring sensors	1	30
TOTAL			**283**

Table 10 - Average consumption power estimated to 283W

5.5 SRS MASS

The bottom-up mass per SRS is estimated to 11,4t, mainly composed of inert material, explaining the feasibility to target competitive cost per kilogram. The structure, membrane and AOCS represent 85% of the total mass (*Figure 8*). The main uncertainty relies on the weight of the membrane, especially its thinness of 4 micrometer (based on NASA study). If not feasible, the weight will increase but it should not affect the launch manifest, as the assumption is to launch 3 SRS/ launch, limited by the volume and not the mass (until SRS mass < 17t).

Subsystem	Item	Quantity	Mass [kg]
AOCS	CMG rotor	2	650
	CGM support and suspension	2	1 000
Structure	Structure	1	4 503
	Reflecting membrane	1	3 178
Communication	Omni-antenna + cables + support	2	2
	Transceiver	2	5
Power	Battery	3	5
	Solar arrays	1	255
	Power management	2	15
Data handling	Computer	2	10
	Sensors (3 STR, 2 IMU)	2	10
	Set of monitoring sensors	1	30
TOTAL			11 365

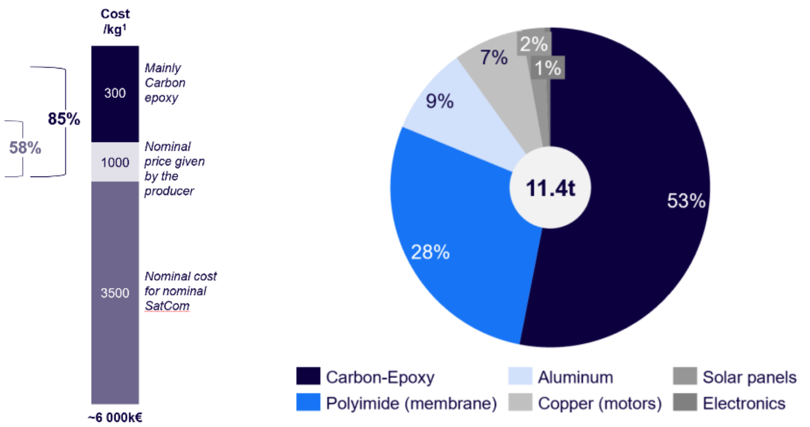


Figure 8 – SRS weight distribution and cost per material

SRS total construction accounts for a negligible part of the space-segment carbon footprint:

- The carbon footprint of producing one ton of carbon-epoxy is 12t CO2e. Considering there is 6t of carbon-epoxy in a single SRS, the total carbon footprint for 3,987 SRS is 287kt CO2e.
- The carbon footprint of producing one ton of PEEK is 28t CO2e. Considering there is 3.2t of carbon-epoxy in a single SRS, the total carbon footprint for 3,987 SRS is 354kt CO2e.

Assumptions on SRS carbon footprint can differ, depending on studies, scope… Yet, it has only a negligible impact on the space-segment carbon footprint which is driven at 99% by launching emissions (50,000t CO2e emitted per launch)

6. MAIN CONOPS FOR SPACE SEGMENT

The main ConOps described in the following pages include five main use cases

1) Launch and deployment to determine which launching strategy to adopt.
2) Assembly process to define how the SRS will be deployed to be fully operational.
3) Attitude control and maintenance to supply spare parts.
4) Collision risk management to evaluate and mitigate the risk of debris collision.
5) End of life to avoid any new debris in space

6.1 LAUNCH & DEPLOYMENT

SUB-SECTION KEY MESSAGES

- Two launch & deployment strategies have been considered, launching in LEO, and using solar sailing is the selected one.
- As the architecture is modular, the launch & deployment plan is fully flexible and resilient to any uncertainty.
- Adding a new DSR to one end of the space train is easier for increasing power than for extending illumination.
- The deployment plan supposes then to first increase the power generated and then increase the illumination period.

6.1.1 LAUNCHING STRATEGY

Two launching strategies have been considered for the DSR concept: Direct to Orbit (DTO) and LEO & Solar Foil (LEO & SF).

- **Direct to Orbit strategy.**
  The heavy launcher vehicle selected for the launching phase is supplied by several SRS or components of SRS under the form of assembly kits. Then several options have been studied:
  - The HLV is programmed to reach the final SSO orbit at 890km and deploys each SRS there.
  - The HLV supplies all the SRS components to a robot platform which assemblies them and each SRS is then transferred to its final orbit at 890km by a space tug (or equivalent)
  - The HLV supplies all the SRS components in its final orbit at 890km where a robot platform is assembling them.

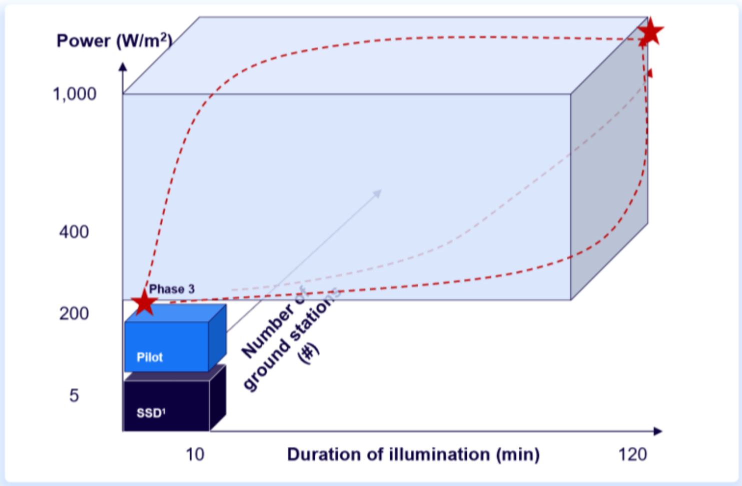
- **LEO & Solar Foil strategy**
  The heavy launcher vehicle selected for the launching phase is supplied by several SRS or components of SRS under the form of assembly kits and is programmed to reach a parking orbit at 680km. Once achieved, SRS / components are unloaded and then unfolded / assembled by a space robot. The final stage for the SRS is to reach the final orbit position at 890km by solar sailing. *Note: the detailed process is described in the ConOps Assembly.*

The LEO & Solar Foil strategy has been selected for DSR concept because it offers an increased payload capacity, which can send to space up to three SRS per launch. This strategy is also preferred because it does not use a space tug, which is costly (production and refueling) and energy consuming.

6.1.2 DEPLOYMENT STRATEGY

As the global architecture is modular with a constellation of mirrors, the deployment can follow an infinite way to reach the full-scale deployment based on three dimensions *(Figure 9)*:

- Increasing the duration of illumination
- Increasing the power delivered on Earth.
- Increasing the number of ground stations receiving the DSR illumination



Note: 1) Sub-scale demonstrator

Figure 9 - Different possible scenarios for the ramp up

However, increasing the duration of illumination or the power delivered on Earth translate differently on the SRS train (*Figure 10*):

- To increase the duration provided on Earth, the principle is to increase the length of the SRS train. With a constant power, it supposes to deploy new SRS at the beginning or at the end of the train to increase the timing over a ground station
- To increase the power provided on earth, the principle is to increase the number of SRS in the visibility window. With a constant duration, it supposes to add new SRS in the already deployed DSR train to increase the density of SRS in the train

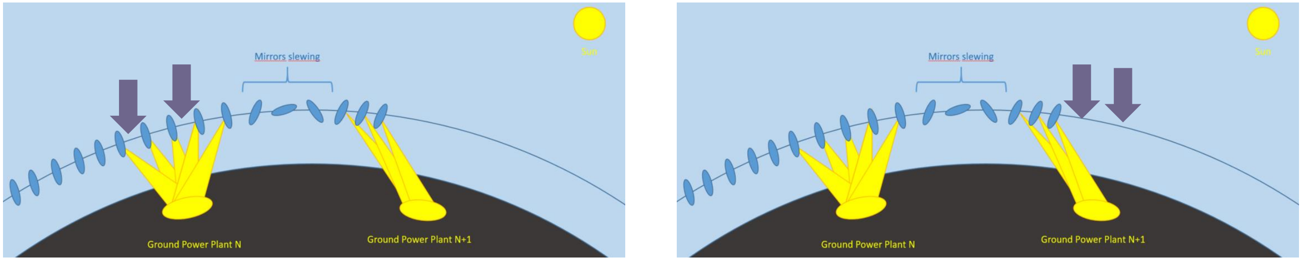


Figure 10 - Adding SRS to increase power (left) and duration of illumination (right)

Because interposing new SRS in the already deployed DSR train could be challenging at a large scale, the selected deployment plan is the following:

- **Phase 1**: Deployment of 107 SRS delivering 200W/m^2 (minimum power to activate a PV cell) for ten minutes on ground stations.
- **Phase 2:** Increase of power to reach 1,000W/m2 while keeping the same duration.
- **Phase 3:** Increase of duration of illumination up to 2h per flight while maintaining the 1,000W/m$^{2.}$
- **Phase 4:** reach 1,000 W/m^2 for 2h

This reference scenario has been designed but it can be modified according to any evolution such as the funding envelop, the technological disruption on space or ground or the production process.

In addition, above 200W/m^2, the efficiency of PV cells is relatively stable *(Figure 11)* and therefore there is a potential room for optimization of the SRS sizing to minimize the weight to launch and be more attractive for ground segment.

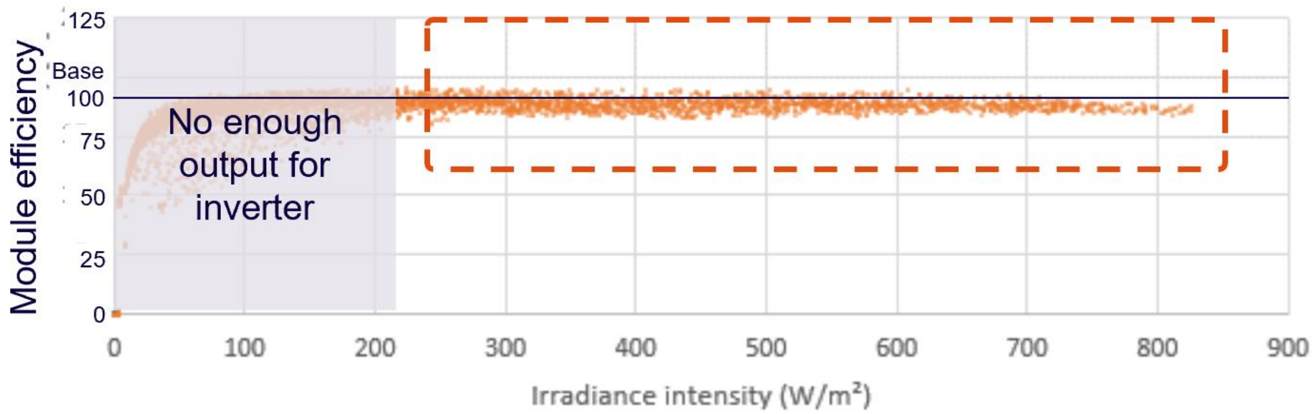


Figure 11 - PV cells efficiency depending on irradiance intensity.

6.2 ASSEMBLY

SUB-SECTION KEY MESSAGES

- The complete assembly sequence is optimized to maximize the load of the launcher and minimize the energy needed with the solar sailing using the mirror surface.
- Assembling the SRS in space needs robots designed to optimize the process: 3 robots in 2 platforms should be enough to support the maximum launch cadence.

An optimized assembly phase is essential to maximize the load of the launcher and minimize the energy needed with the solar sailing using the mirror surface. The process from launch to is decomposed in 11 phases from the launch to the reflector insertion in final orbit (*Figure 12*):

1. **Launch**

The launch time and injection accuracy are critical to avoid postponing the rendez-vous to the next opportunity. A cadence of a launch every 3 days is projected, each launch sending 3 reflectors.

2. **Upper stage injection**

The launcher injects the upper stage and its payload on a specific parking orbit where the robotic space tug is waiting for it. The upper stage is in charge of the orbital phasing maneuvers in absolute navigation.

3. **Upper stage docking with space tug**

The robotic space tug performs a closing approach in relative navigation up to the docking. The upper stage shall remain steady in attitude control while robotic space tug maneuvers to dock to it.

4. **Payload recovery**

Once docked, the robotic space tug, if needed, refuels itself from upper stage's tanks and proceeds with the payload extraction. The payload consists in a cluster of three maximum reflectors elements organized to optimize both the fairing volume and the assembly sequence.

5. **Empty upper stage separation and re-entry**

Once the payload cluster is recovered by the robotic space tug, the upper stage performs a de-orbiting maneuver: if demisable, it will perform a controlled re-entry and burn in the atmosphere and if reusable, it will be recovered and refurbished for another launch.

6. **Robotic assembly**

The robot of the space tug proceeds to reflector kit assembly by picking up elements of the payload cluster and building the reflector one piece at a time. This is a 4-day full time robotic work for the assembly of a single reflector.

7. **Folded reflector separation with a space tug**

Once the reflector assembly is completed, the robotic space tug proceeds to reflector separation by pushing it at the maximum robotic arm reach and by using its thrusters to get distance between the spacecraft. It is preferred not to perform the reflector deployment when it is still docked to the space tug (and the other potential reflector kits) to avoid attitude and orbital disturbances due to the large structure. This phase is expected to take a day per reflector.

8. Reflector deployment

Once separated, the reflector starts its deployment sequence which will probably take a few tens of hours to deploy the structure and the reflecting membrane and then it starts its attitude control systems. In case of problem, the robotic space tug is still near and could perform reflector recovery. Deployment is expected to take a day per reflector.

9. Robotic space tug towards next rendez-vous zone

Once all of the reflector kits are assembled and dropped, the robotic space tug can move towards its next rendez-vous zone. This motion is not necessarily based on costly maneuvers but can be a combination of maneuvers and long drift periods.

10. Reflector solar sailing orbit raising

Immediately after its deployment, the reflector performs attitude control to orientate the reflecting surface to provide thrust for a solar sail orbit raising. The duration of this phase has been estimated at approximately 50 days per reflector.

11. Reflector insertion in final orbit

Once final orbit has been reached, the reflector shall orientate the solar sail thrust to insert itself in the reflector train position. This is a very critical maneuver because reflectors are only 12 km away from each other; the best is to add new reflector at the head or tail of the train to avoid complex insertions.

At full cadence for deployment, the TAKT time of the supply chain should be about 3 days and the in-orbit facilities are sized to respect this timeframe: 2 platforms of 3 robots each, a robot assembling a SRS every 4 days.

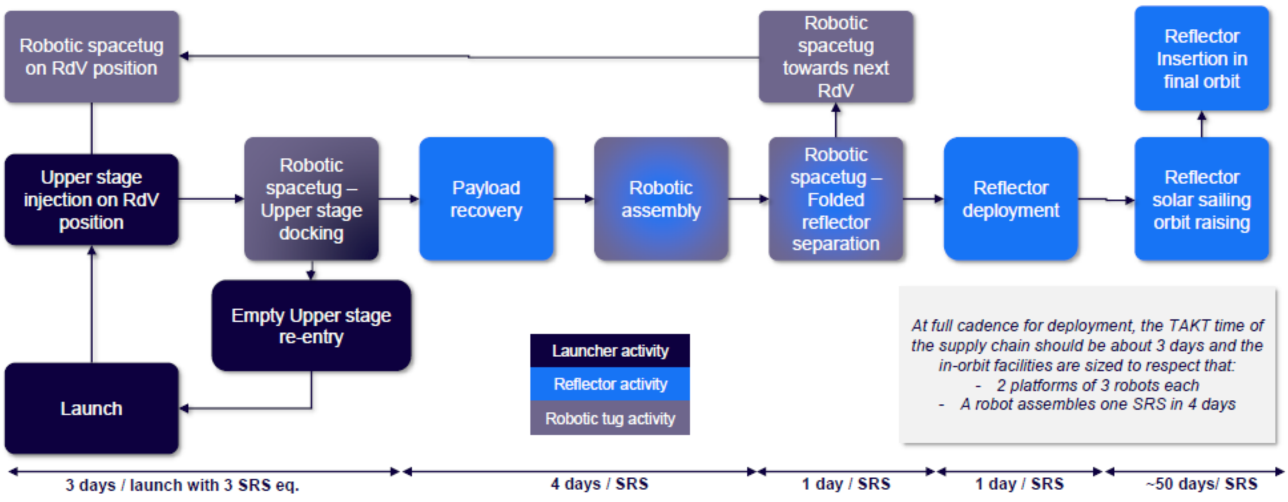


Figure 12 - Assembly process for a single DSR

6.3 ATTITUDE CONTROL & MAINTENANCE

Over the SRS lifetime, maintenance operations will be needed to ensure the integrity of the membrane and structure and therefore the good performance of the reflector. Maintenance operations have been summarized in the *Table 11* below.

Operation	Description	Frequency	Tool & Process	Material needed
Change of parts of the service module	Electronic card, battery, CMG…	Every 15y	• Robot extracts the card and plug the new one	Electronic card, battery cells
Mirror reparation	From small debris (micro-meteorite)	On demand	• 24/7 camera to detect holes • With holes, release cables to decrease tension • Robot crawls on the mirror and sticks a patch or change a complete triangle	Mirror surface
Beam reparation	From small debris (micro-meteorite)	On demand	• Replace each one	New beam
Robot reparation	Change and/or repair parts a robot	Every 10y	• Change & replace old robots	Robot
Change of the complete service module	Change the service module of SRS if needed	On demand	• Robot will declip the service module from the mirror and plug a new one	Service module
Robotic space tug refueling	Robots and platforms need to be refuelled	Every year	• Robot will grap the fuel tank in the launcher	Fuel tank

Table 11 - Maintenance plan for the space architecture

6.4 COLLISION RISK MANAGEMENT

SUB-SECTION KEY MESSAGES

- Such large platforms raise the question of collision risk with space debris and meteoroids.
- There is a real concern on collision risk & mitigation as impacts could generate a poor system availability and robotic repair systems on each reflector.
- Due to its speed, even a small debris will create holes in the reflecting surface, leading to decrease the reflecting performance and its robustness.
- On membrane, it makes a cumulated number of 74.6 billion of penetrating impacts, i.e., an average of 9.5 impacts piercing 1 cm² after 10 years.
- Fixing this critical issue could lead to pivot the DSR concept.

Such large platforms raise the question of collision risk with space debris and meteoroids which could significantly deteriorate the space architecture and therefore the reflecting performance. Improvements in Space Situational Awareness are expected in the near future. For instance, over the next decades, it should be possible to detect any object above one centimeter and issue a warning message with a very thin uncertainty thanks to space surveillance sensors and orbit propagators improvements. It could reasonably reduce the uncertainty of the collision point on the reflector to a few tens meter-square-large area.

Regarding the larger debris, 3 potential collision risk strategies have been identified:

- **"Let it be"** by estimating that given the debris energy and the probable zone of collision, it is acceptable to let the collision happen
- Perform an **attitude correction** to minimize/nil the collision risk or its potential damages
- Perform an **orbital correction maneuver** to minimize/nil the collision risk or its potential damages

For smaller debris and meteoroids that elude any detection mean, a statistical analysis with DRAMA was performed for an orbit altitude between 800 and 900 km. The analysis demonstrated that there is 100% probability of collision with objects of up to 2.5 mm after 10 years, and no collision risk with objects bigger than 7 mm. It also showed that over 10 years, the structure should have 70 collisions with debris or micrometeoroids of 1 mm, and up to 700 collisions for debris slightly smaller (0.7 mm). The *Figure 13* illustrates the effects that could have these impacts on the carbon fiber-epoxy structure. It is also to be noticed that any impact of these small debris will in fact reduce the number of debris as the speed of much smaller pieces will strongly decrease.

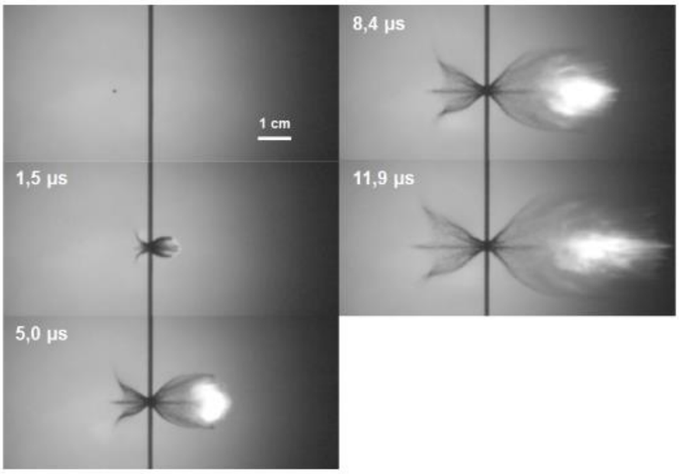


Figure 13 - Fast imaging of a 1 mm Al6061 bullet impacting a carbon fiber-epoxy target at 5.62 km/s and resulting debris cloud

Analysis performed with DRAMA have raised a critical issue about collision risk: the membrane could receive a cumulated number of 74.6 bn of penetrating impacts, i.e. an average of 9.5 impacts piercing 1 cm² after 10y (*Figure 14*).

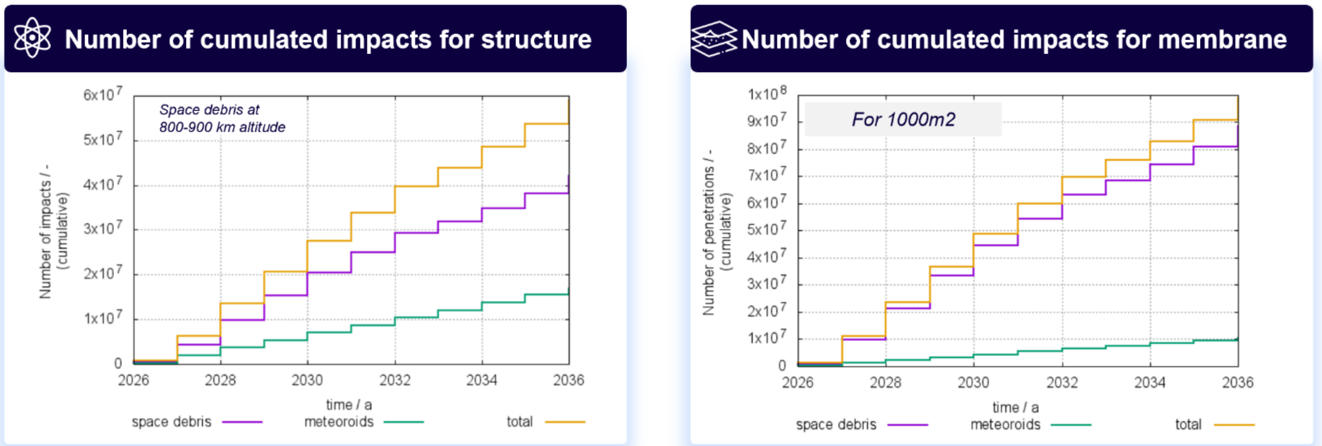


Figure 14 - Number of cumulated impacts over 10 years on structure (left) and membrane (right)

The impacts from very little debris will still cause small damages on the surface: 10% of losses in 30y with average impacts of 10µm, ~0.3%/year of the surface. To maintain the integrity of the membrane, it has been assumed to change 5% of the deployed mass every year.

Though, a specific mitigation plan has to be deeply defined to ensure it will not threaten the global performance. Strategies to mitigate these effects should be more deeply assessed by estimating the amount of spare parts needed over the SRS lifetime or the replacement rate of certain components. Alternative strategies to fix the collision critical issue have also been analyzed:

- **Use of self-healing material *(not selected)***

This strategy is interesting because polymers could be repaired in case of damages. However, it is only applicable for surface deformation and not with holes in the surface and with thin films.

- **Use of plasma to inject material in the surface *(not selected)***

Plasma is an ionized gas that with a precise voltage can be direct to a specific area. Yet, it is not applicable with holes in the surface and with thin films and it supposes to generate energy to create the plasmas.

- **Deposit of patches *(to be further analyzed)***

This strategy makes the use of a robot (mobile or fixed to the mirror) which takes a pre-aluminized patch in a batch and sticks it to cover the hole. It though presents a major inconvenient: the number of impacts by SRS is not compatible with the stock of patches to manage in the long term globally. However, it could be possible to stick patches for larger impacts and keep small damages for very small impacts.

- **Reconsider the orbit altitude to deploy the mirrors in GEO with Coherent Light technology *(to be further analyzed)***

The security issue of this technology must be fixed as it could represent a red flag for ESA program. A potential solution to this problem has been proposed in *Section 10. Technology development requirements*

6.5 END OF LIFE

SUB-SECTION KEY MESSAGES

- Different possible strategies for end of life should be combined to avoid any new debris. Recycling should be possible in 30 years
- The approach is to focus on the recycling/ refurbishing capabilities

DSR is anchored in a strategy to achieve a positive environmental impact, and the management of end-of-life debris is therefore essential. Five end-of-life strategies have been studied:

- **No end of life, SBSP is maintained forever**
  The cost of exploiting the SBSP for more than thirty years is to maintain it in operational conditions the system. However, it is not really satisfying as it is extremely costly and as one day a new power production will certainly be more efficient than SBSP, like nuclear fusion or equivalent.

- **Decommissioning and place in a graveyard orbit**
  This is a classical approach in which after operational life, the spacecraft is placed, by itself or thanks to a space tug, to an orbit on which it could not interfere with current or future mission. The definition of graveyard orbits is subject to change, and it is hard to anticipate what could still be allowed in several decades. This strategy is not possible in LEO orbit and has been excluded.

- **Design for recycling/refurbishing**
  In this approach, the space segment is designed to be recycled or refurbished in space. Used parts car be dismantled and stored in a space warehouse waiting for recycling. The recycling space factory could use solar power to melt, separate and transform materials, for example in a centrifugal solar furnace. Design for recycling supposes that the space segment uses only recyclable materials in its conception and its architecture will ease the dismantling process. If it is the best approach, it supposes also to deploy specific facilities in space to manage the end-to-end process, that will take decades to be operational

- **Natural orbit decay and burn in atmosphere.**
  This is also a today practice but it is not sure to be still allowed in the future due to sanitary reasons (in cause the small particles spread in the atmosphere during re-entry burn). This solution is simple for large and lightweight platforms like reflectors for which the drag force acts significantly in LEO.

- **Dismantling and controlled re-entry to Earth**
  This approach consists in dismantling the space infrastructures and take them back on Earth in the cargo bay of reusable upper stages which otherwise would have returned empty. It implies a considerable spent of energy, but this is the cost for a much more virtuous space usage than simply burning things in the atmosphere.

The preferred solution is the reuse and recycling of materials to minimize the debris produced.

On the long term, design for recycling/refurbishing is the most promising policy as it avoids any waste. It will allow to maintain the structure in orbit and a deployment of recycling system will be implemented in orbit. However, the TRL is still very low (TRL = 1).

Recycling supposes a cost for processing, but the material could potentially be resold to third parties or reused for spare parts of the DSR architecture. The estimated cost is still very preliminary and should be better estimated in the coming years, when recycling platform will be better defined. Furthermore, the material that could be used for component will be selected to offer the best compromise cost/ sustainability/ possibility and will be tested during the demonstrator phase.

The end-of life policy is summarized by space architecture component in the *Table 12*.

Component	End-of-Life Policy	Rationale	Risk
Mirror	• Recycling the material could be interesting to limit the replacement of reflector	Large flat with very low density	Low
Beam	• Can be reused for new DSR • Controlled re-entry on Earth	Relatively low density but solid with potential long lifetime	Low
Service module	• Change electronic card (plug & play)	Small service module could be reused with new electronic cards	Low
Robot	• Controlled re-entry on Earth	Avoid any new debris	Low
Tug & platform	• Material recycling	Avoid any new debris	Low
Fuel tank	• Material recycling	After refueling, the tank can use the return trip of a launcher	Low

Table 12 - End of life strategy per component in space

7. LAUNCH & DEPLOYMENT PLAN

SECTION KEY MESSAGES

- The launch capability is a critical bottleneck for DSR, either for capacity, costs and for environmental matters
- Based on discussions with PROTEIN leaders, we have considered to limit the load of launchers to 3 SRS maximum, Ariane 64 allowing to launch some prototypes before
- The guideline of the deployment plan of the DSR architecture is to deploy as soon as possible, using the full capacity of PROTEIN and extra capacity of Starship to reduce the time to market.
- First launches could happen in 2032 and full-scale deployment released in 2043.

7.1 THREE LAUNCHERS CONSIDERED

The launch capability is a critical bottleneck for DSR, either for capacity, costs and for environmental matters. Three launchers are considered for the concept: Ariane A64, Starship, PROTEIN, each showing benefits and drawbacks.

7.1.1 ARIANE A64

Ariane A64 is a European based launcher which is projected to make an inaugural flight mid-2024. In addition, it offers a large volume under-fairing ($905m^3$). Yet, it has a maximum payload capacity of 21 tons (in LEO & Solar Foil policy) limiting the number of SRS that can be sent per launch to only one and incurring high costs for the launching phase.

Because of its near availability to market and location, Ariane A64 would be used for the sub-scale demonstrator.

7.1.2 STARSHIP

The launcher developed by SpaceX offers a large volume under-fairing and high payload capacity (up to 100t in LEO orbit), which makes it possible to send three SRS per launch and therefore to decrease the cost per kilogram sent to space. However, Starship is based in the United States and its capacity could not be entirely dedicated to the DSR deployment.

However, Starship could be used for the scale up plan to accelerate the deployment before the full availability of PROTEIN.

7.1.3 PROTEIN

PROTEIN is a European based heavy launcher under development. Once operational, its capacity and cadence is considered as fully dedicated for DSR deployment. PROTEIN consortiums are working on a CCN to fit their respective launcher with SOLARIS needs by developing a vehicle able to send three SRS per launch as Starship. Yet, PROTEIN is still in development and is not expected to be available before 2030 and fully operational before 2035-2040 (depending on the consortium).

PROTEIN will be used for the scale-up plan at the maximum cadence.

7.2 LAUNCH & DEPLOYMENT ASSUMPTIONS

7.2.1 CAPACITY AND COST ASSUMPTIONS

Based on our discussions with PROTEIN, we have considered to limit the load of launchers to three SRS maximum (explaining why Starship has a capacity of 58t in LEO&SF) and Ariane A64 will launch some prototypes before. The assumptions taken all three launchers have been summarized in the *Table 13.*

	Launching capabilities					Launching cost performance		
	Direct to Orbit	LEO & Solar Foil	Volume under fairing	SRS sent per launch	Cadence	TTM	Initial recurring cost	Cost CAGR
	tons	tons	m^3	# SRS / launch	Launch / year	year	m€	%
Ariane A64	14.0	21.0	905	1	8	2029	100	-2%
Starship	49.0	58.0[1]	664	3	100	2025	100	-5%
PROTEIN	49.3	51.0[2]	1,500	3	100	2035	20[3]	-2%

Note: 1) To limit to 3 SRS ; 2) For 680km, 98° of inclination: lowest value of the two PROTEIN projects: 51 tons & 64 tons; 3) Target recurring costs for ESA in 2035 < 280€/kg

Table 13 - Launching capabilities and cost performance assumptions.

7.2.2 LAUNCHING PLAN

The objective is to deploy the 3,987 SRS as soon as possible. In this context, two alternatives (*Figure 15*) will be assessed:

- **Option 1: PROTEIN ONLY**

In this scenario, only PROTEIN launcher will be used at the maximum available cadence based on its ramp-up. The deployment is expected to start in 2032 and to be done by 2047.

- **Option 2: PROTEIN + 50 STARSHIP IF NEEDED**

In this scenario, in addition to PROTEIN launcher used at the maximum available cadence, 50 Starship launchers per year will complete the deployment plan, accelerating the deployment by 4 years (2043)

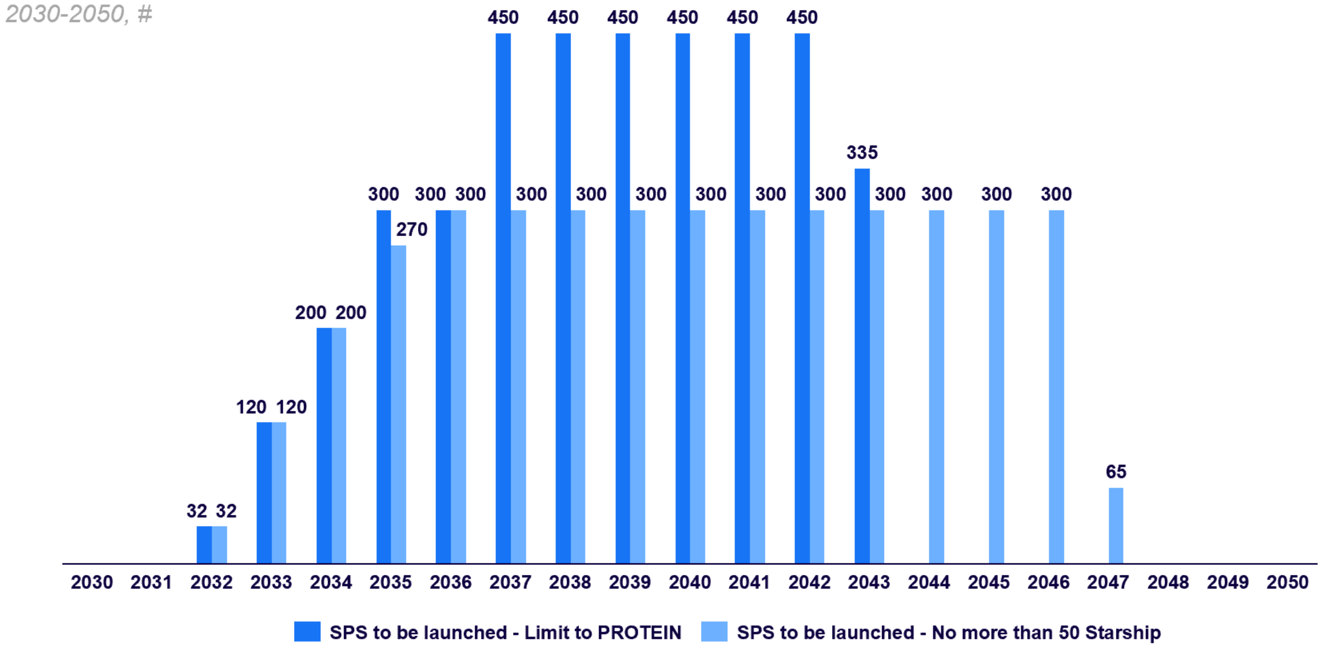


Figure 15 - Number of SRS to be launched per year.

7.2.3 LAUNCHING MANIFEST

Launching costs have been estimated for the two deployment options (excluding the sub-scale demonstrator phase). They include the global recurring costs for deployment and maintenance:

- The costs for launching the full space infrastructure. DTO and LEO & SF have same launched costs but DTO supposes complex loading of the launcher for 3 SRS and therefore LEO & SF strategy is more resilient.
- It has also been assumed that 5% of mirrors need to be replaced every year at a cost of 1m€ each, representing on the project lifetime of 30 years 5,973 mirrors of be changed for a total cost of 11.7bn€

It does not include the launching costs for deploying the robots and platforms as it is of second order of magnitude at this stage.

Following the deployment plan in *Figure 15*, the key outputs for the two launch scenarios (PROTEIN only and PROTEIN & Starship) are summarized in the *Table 14* below. Launching manifest remain the same whatever the launching strategy selected between DtO and LEO & SF.

	Unit	Option 1 PROTEIN only	Option 2 PROTEIN + Starship
A64	#	-	-

Starship	#	88	410
PROTEIN	#	1,242	920
Additional launches for maintenance	#	364	361
Total number of launches	**#**	**1,694**	**1,691**
Global recurring costs (non-discounted)	**m€**	**39,101**	**45,604**
Average launching costs per kg	**€/kg**	**861**	**1,004**

Table 14 - Launching manifest key outputs.

Deployment Option 2 (PROTEIN + Starship) is privileged to accelerate the time to market by four years, however, using extra capacity of Starship adds additional €6.5bn of RC that must be leveraged in revenue.

8. ASSESSMENT OF THE SYSTEM PERFORMANCES

SECTION KEY MESSAGES

- Global space to ground model includes factors based on the DSR configuration but most of the attenuation is correlated with ground segment location and configuration.
- The ratio from space to ground can vary from /9 to /14 depending on the location and configuration of the ground station.
- The SRS train will illuminate an ellipse of 17km x 53km axis with a light intensity of at least an overcast day, allowing to activate PV cells under this surface.

The system performance is assessed by comparing the power delivered by the sun illumination with the actual energy generated which can be sold. Power attenuation factors are detailed in the *Figure 16* and depends either on the DSR architecture or on the ground station location and configuration.

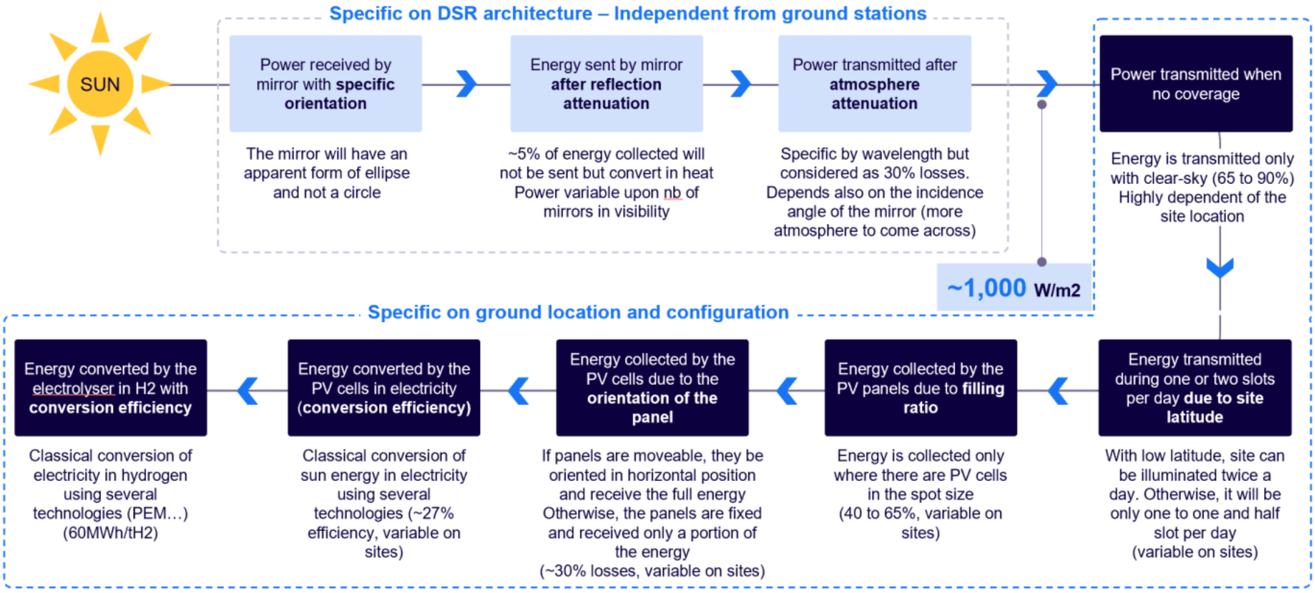


Figure 16 Space to Ground performance.

Attenuation factors specific to DSR architecture

The sun delivers a power of 1,360W/m^2 to the DSR architecture, which itself sends 1,000W/m^2 to ground station. This loss of approximately 25% is explained by:

- The specific orientation and elliptical form of the mirror: As the mirror is not purely perpendicular to the sun, the energy collected is not purely linked to the surface mirror, but its apparent surface seen by the sun.
- A reflection coefficient of 95% meaning that 5% of energy collected will not be sent but convert in heat in the reflector surface[6]

[6] The rationale of this parameter and others are explained in the last part of the document.

- The atmospheric attenuation which is specific to wavelength and slightly depends on the incidence angle of the mirror. Indeed, when the elevation angle of the reflector is low, the illumination sent must go through a higher distance with atmosphere.

Based on this attenuation factors, the DSR has been designed to send 1,000W/groundm2, before factors specific to location and configuration of the GPS, as described below.

Attenuation factors specific to ground location and configuration

1,000W/m^2 are delivered by the DSR architecture to the ground station, which is then subject to attenuation ratio depending on ground stations. The loss can be explained by:

- The coverage ratio which is highly dependent on the site location. Power is transmitted only with a clear-sky.
- The site latitude since low latitude sites can be illuminated twice a day, otherwise, it will only be one to one and half slot per day: with high latitudes, the GPS will receive natural sun during summer, and no sun in winter. During winter, DSR can illuminate 2x2h, and in summer, DSR can illuminate to compensate the natural sun power until 1000W/m2. We consider in this case that the average illumination is 3h/day.
- The filling ratio of the station, meaning the surface covered by solar panels in the spot size generated by DSR.
- The panel orientation: The power effectively received by the panel on the ground is linked with the angle between the panel and the illumination sent by DSR.
- The efficiency ratio of PV which is the capacity to convert sun energy into electricity. It is worth today 27% and could continue to increase in the next years
- The efficiency ratio of electrolysis which is the capacity to convert electricity into hydrogen. Today 60MWh are required to make one ton of hydrogen (including the energy needed to manage the water supply)

To illustrate the impact of these attenuation ratio on the system performance, a space to ground model has been designed for three different scenarios:

- The minimum scenario for a nominal PV plant area of 7km^2 → *assumptions taken for a small ground station in the business case, as it is the average area of PV stations with moving panels and low latitude.*
- The minimum+ scenario for a maximum production of 1GW on an area of 7km^2 with fixed panels and a station located in high latitude
- The maximum scenario for a PV plant compatible with the DSR spot size of 8km diameter, corresponding to a surface area of 50km^2 → *assumptions taken for a large ground station in the business case.*

Attenuation ratios assumptions vary between the scenarios and are summarized in the *Table 15.* A large ground station is expected to generate 5.6 GW of electricity out of the 50.3 GW received from DSR, representing an attenuation ratio of 9x. Small ground station have a less satisfying performance because of a higher coverage attenuation and a lower filling rate resulting in an attenuation ratio of 14x: out of the 6.2 GW delivered by DSR, a small ground station generate only 0.4 GW of electricity.

	Unit	Scenario Min	Scenario On Grid	Scenario Max
GPS area	km^2	7	7	50
Solar constant	W/m^2	1,360	1,360	1,360
Power emitted by DSR to Earth after reflection & atmospheric attenuation	W/m^2	882	882	1,000
	MW	6,234	6,234	50,265
Power after coverage attenuation	MW	4,052 (65%)	4,052 (65%)	45,239 (90%)
Power after filling rate[7]	MW	1,621 (40%)	2,634 (65%)	29,405 (65%)
Power after incidence angle[8]	MW	1,621 (100%)	1,870 (71%)	20,878 (71%)
Electric power generated	**MW**	**438 (27%)**	**505 (27%)**	**5,637 (27%)**
Attenuation ratio	*x*	*14*	*12*	*9*
Daily illumination duration	h	4	2	4
Annual energy generated	**GWh**	**639**	**369**	**8,230**

Note: The percentage indicate the share of retained power

Table 15 - Space to Ground model

At peak elevation, the SRS will illuminate a spot size diameter of around 8km. Yet, the sum of the illumination of the 257 SRS in visibility (with lower elevations) will illuminate an ellipse of 17km x 53km axis with a light intensity of at least an overcast day, allowing to activate PV cells under this surface (***Error! Reference source not found.***). However, as the transmission is “natural”, an intensity less than t he sun one will strongly reduce the environmental impact and the light pollution, both on the ground and for the night sky, and both for illumination of GPS as well as for the slewing in between GPSs.

[7] Ratio between the ground size and the area covered by panels. Fixed panels have higher ratio.

[8] 100% = moving panels, 71% = fixed panels considered at 45° of latitude

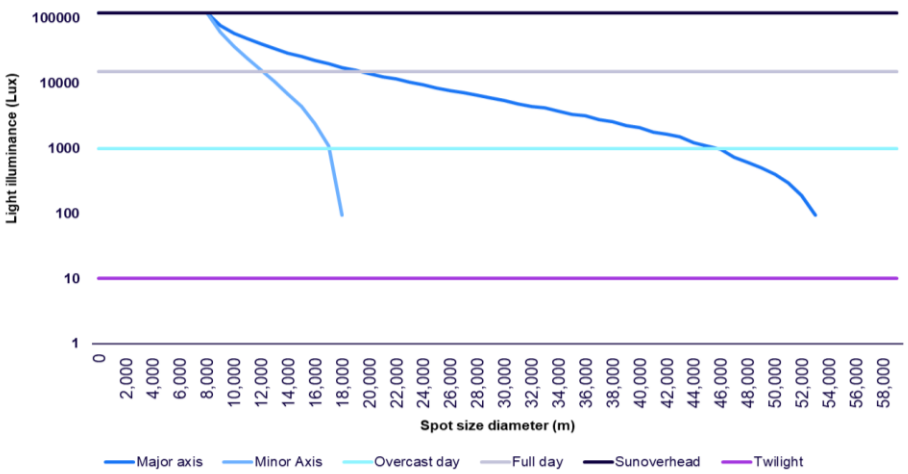


Figure 17 - Light intensity vs spot size diameter

9. DESCRIPTION OF THE GROUND SEGMENT

9.1 GROUND SEGMENT TYPOLOGY

SUB-SECTION KEY MESSAGES

- DSR can illuminate several ground configurations and technologies that all are compatible with the concept.
- Each type of these ground stations will benefit in the future of incremental or disruptive technology innovations to boost their competitiveness.
- There are potentially more than 15k solar farms that could benefit from our DSR concept.
- A trend towards the construction of larger solar power plants with increased production capacity is being observed worldwide, in line with the needs of DSR.
- Solar fuel technologies, also known as sunlight-to-X, convert solar energy directly into chemical energy in the form of liquid or gaseous fuel.
- The monolith process of turquoise hydrogen could even have a better yield rate than solar fuel.
- Large players are already active in the hydrogen market and could be interested to leverage the DSR concept to increase energy without additional CAPEX.

The DSR train can illuminate any station covered by the selected orbit using natural illumination from the sun. The business case is based on 3 main types of stations:

- **Classical PV stations** for facilities in Europe and connected to the grid. PV is a mature technology
- **PV stations combined with an electrolyzer** for outside Europe, which has a medium level of technology maturity
- **Solar fuel cells** as it could be a very promising technology to increase the efficiency rate for producing hydrogen since they convert solar energy directly into chemical energy in the form of liquid or gaseous fuel. As of today, SFC technology is still under development and has a low maturity level but the process could have a yield rate of 40% for producing green hydrogen by 2040

Each type of these ground power stations will benefit in the future of incremental or disruptive technology innovations in terms of materials or processes which will allow to boost their efficiency and competitiveness.

As of today, more than 7,000 solar farms are operating worldwide, almost another 7,000 are under construction and more than 1,300 project have been announced. It has been observed over the last decades a trend in favor of larger solar power plants with increased production capacity (*Figure 18*) that will benefit the DSR program as it requires a large spot size on the ground and capacity needs.

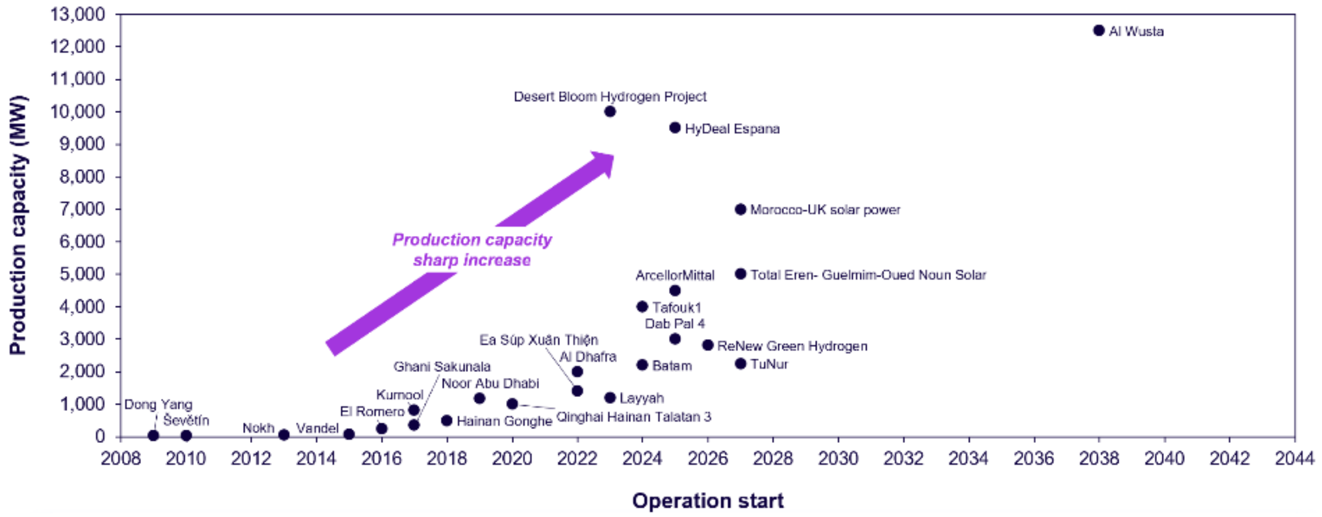


Figure 18 - Production capacity of solar power plants over years

Furthermore, the demand for energy and especially hydrogen will sharply increase over the next decades (*Figure 19*). Large players are already active in the hydrogen market and could be interested to leverage the DSR concept to increase energy without additional CAPEX *(Figure 20*). The demand for hydrogen will grow at a 7% CAGR between 2020 and 2050, which is faster than the electricity demand CAGR of 3%. Therefore, hydrogen will represent a higher share of the energetic mix (+19pp between 2020 and 2050, including hydrogen for electricity generation):

- In 2020, 5,220 TWh (87Mt) of hydrogen have been consumed
- By 2050, it is projected to raise to 31,620 TWh (527 Mt), among which 6,120 TWh (102 Mt) will be stored to be later transformed into electricity

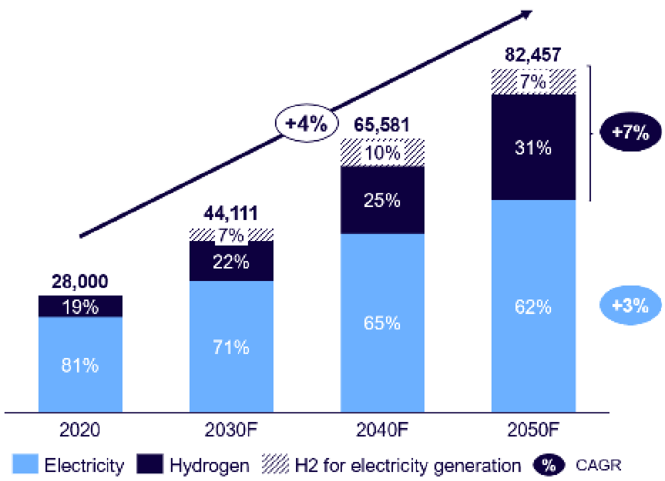


Figure 19 - Total electricity & H2 based-fuels consumption

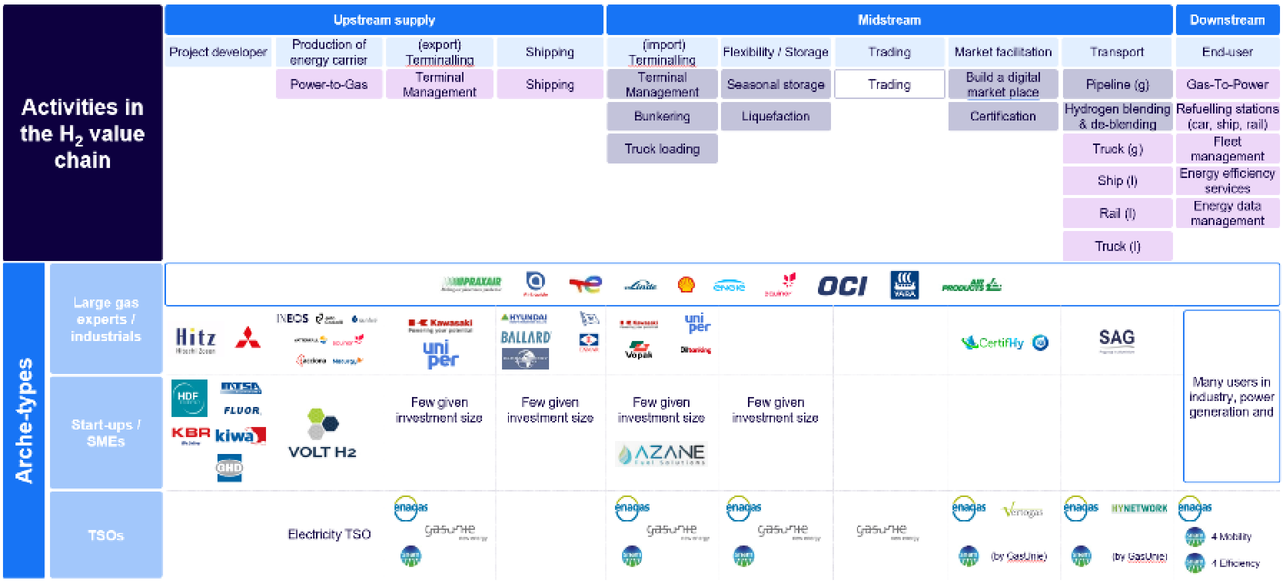


Figure 20 - Existing players by hydrogen value chain activity

Other technologies than the 3 cited above (PV, PV+ELY, SFC) can also be leveraged, like turquoise hydrogen that can even have a better yield rate than SFC. “Turquoise” hydrogen is formed from methane that is fed into a reactor, which heats it to a high temperature (~2,000°C) in the absence of oxygen. In this process, the methane breaks down into hydrogen (H2) and solid carbon black (C), while avoiding the production of CO2 in return. Carbon black is mainly used in tyres, but also in dyes, paints, batteries, and cells. This by-product makes the process economically interesting as it could be resold. Today, the production of “turquoise” hydrogen is close to the emission level of “green” hydrogen (0.03 to 0.37 kg CO2e/kg), but it is 3 times less energy-intensive, a figure that could theoretically rise to 7 with improved processes. If the reactor is fueled entirely with biogas from household waste, the carbon intensity drops to -5.22 kg CO2e/kg. In a scenario where fossil gas and biogas are mixed, only 10% biogas is sufficient for zero carbon intensity.

9.2 GROUND SEGMENT USE CASES & BENEFITS

SUB-SECTION KEY MESSAGES

- DSR architecture is a key enabler for ground operators to increase their performance and revenue.
- Two main use cases and value proposition to ground operators as third parties.
- Our value proposition to on-grid ground operators has been designed to be more attractive than existing storage solutions, especially for utility size.
- Off grid H2 operators use case: Boosting energy produced without additional CAPEX.
- DSR provides a high impact of energy production for any sun-based ground operator – in case of PV on grid, the value is mainly based by selling energy at the peak hours.
- The impact of DSR on PV plants1 mitigates their negative impacts and restore their competitiveness compared to other renewable energy.

DSR architecture is a key enabler for ground operators to increase their performance and revenue regardless the type of station (PV, PEM electrolysis or SFC). At full scale, it is estimated that DSR can provide 40-60% additional energy (in addition of energy delivered by the sun natural illumination) and therefore revenues, without increasing CAPEX for storage or extra capacity. In addition, DSR use cases and value proposition differ depending on the GPS grid connection.

9.2.1 ON GRID PV OPERATOR

DSR can maximize the utilization of installed capacity and can help managing intermittency for the grid, by providing a stable source of electricity. DSR has also the capability to provide maximum energy output precisely when intraday electricity prices are at their highest, optimizing financial returns. Indeed, on grid PV operators can be supplied additional irradiance at dawn and dusk periods allowing them to resell energy when demand and prices are the highest rather than using costly storage systems to keep the energy produced during low consumption period or lose it *(Figure 21**Error! Reference source not found.**)*.

To reach the same level of energy production without DSR, the PV operator would have to either increase the installed capacity which is very costly and limited by the station area, increase the filling rate or switch to PV panels with higher conversion rate to enhance efficiency. Aside from that, the cost of development of the storage solution for the addition production must also be considered.

The analysis for one single PV station of 50 km^2 with an installed capacity of 8.8 GWp has been made and outputs are illustrated on *Figure 22* (all values are discounted). The WACC is assumed to be 7%. Based on these assumptions, at natural illumination 165 TWh of electricity are produced over a 30-year-lifetime for a TCO of €2.6bn and LCOE is worth 19 €/MWh. With DSR, an additional 35% of electricity is produced to reach 223 TWh. If the additional energy delivered by DSR is sold for free, TCO would still be the same and LCOE would decrease to 12 €/MWh.

DSR value proposition to on-grid operators must be more attractive than existing storage solutions, especially for utility size. According to IEA, storage solutions for utility operators would cost between 100 to 200 $/kWhp in 2040. A transfer price between SpaceCo and on-grid PV operator of 80€/MWh equivalent has been taken for purpose of this study, which is assumed to be attractive for on-grid ground operators to avoid costly storage systems.

With a transfer price of 80€/MWh equivalent, TCO amount €7.3bn and LCOE 33 €/MWh for 223 TWh of electricity produced. To reach this same volume of production without using DSR, it would require €8.3bn, including an investment of €4.7bn in storage capacity. Therefore, a PV operator can save up to €1bn by exploiting the energy from DSR system.

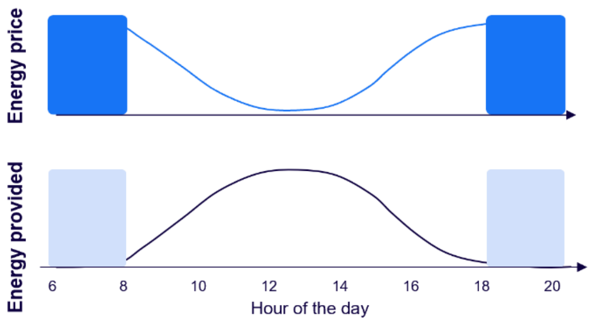


Figure 21 - DSR use case for on grid PV operator

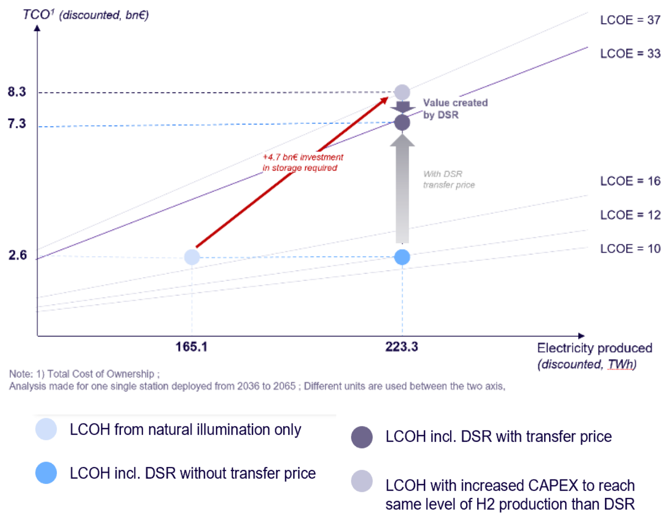


Figure 22 - LCOE analysis for one single PV station (considering ramp-up)

9.2.2 OFF GRID PV & H_2 OPERATORS

For off-grid operators (mainly H_2 producers such as PEM electrolysis or SFC operators), DSR could contribute to increase the volume of hydrogen produced without additional CAPEX, resulting in an increase of the return on capital employed *(Figure 23)*

Like an on-grid PV operators, to reach the same level of energy production without DSR, high financial investments must be made to increase the installed and storage capacity. In addition, SFC is still in early-stage development and the technology would also have to be industrialized on larger scale to increase production.

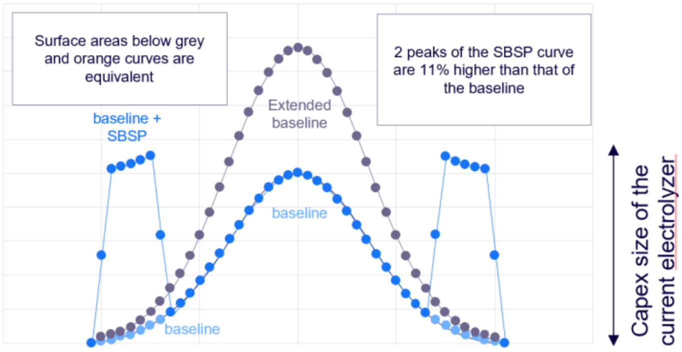


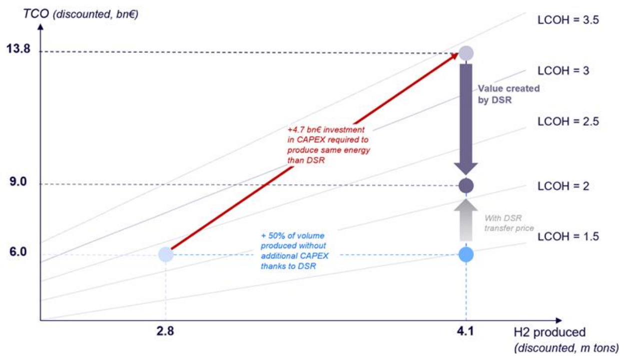
Figure 23 - DSR use case for off grid ELY operators.

The analysis for one single PV with electrolysis station of 50 km^2 with an installed capacity of 8.8 GWp has been made and outputs are illustrated on *Figure 25* (all values are discounted). The WACC is assumed to be 7%. Based on these assumptions, at natural illumination 2.8m tons of hydrogen are produced over a 30-year-lifetime for a TCO of €6.0bn and LCOH is worth 2.3 €/kg H_2. With DSR, an additional 50% of electricity is produced to reach 4.1m tons of hydrogen. If the additional energy delivered by DSR is sold for free, TCO would still be the same and LCOH would decrease to 1.5 €/ kg H_2.

With a transfer price of 40€/MWh equivalent between SpaceCo and the PV with electrolysis operator, TCO amount €9.0bn and LCOH 2.3 €/kg H_2 for 4.1m tons of hydrogen produced. To reach this same volume of production without using DSR, it would require €13.8bn, including an investment of €4.7bn in CAPEX. Therefore, a PV with electrolysis operator can save up to €5bn by exploiting the energy from DSR system and decrease its LCOH by approximately 30%.

This analysis has also been conducted for a SFC operator *(Figure 24)* with the same ground station configuration (50 km^2 of surface area and 8.8 GWp of installed capacity). The WACC used in this case is 9%, higher than the WACC for PV and ELY stations because of the low technology maturity. At natural illumination, a SFC station produces almost twice as more hydrogen than a PV with electrolysis station: 5.6m tons of hydrogen are generated from the sun light for a €9.8bn TCO and 1.8 €/kg H_2 LCOH. DSR can increase by 50% the energy production to reach a volume of hydrogen produced of 7.5m tons.

With a transfer price of 40€/MWh equivalent between SpaceCo and the SFC operator, TCO amount €12.4bn and LCOH 1.7 €/kg H_2 for 7.5m tons of hydrogen produced. To reach this same volume of production without using DSR, it would require €19.8bn, including an investment of €7bn in CAPEX. Therefore, a PV with electrolysis operator can save up to €7.4bn by exploiting the energy from DSR system and decrease its LCOH by approximately 40%.



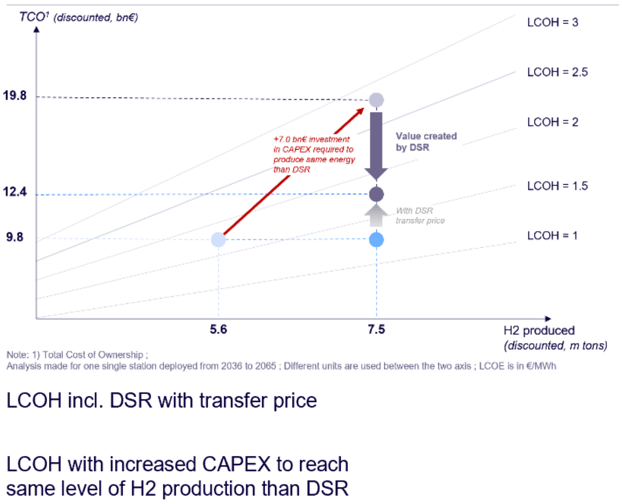


Figure 25 - LCOH analysis for one single PV + ELY station (considering ramp-up)

Figure 24 - LCOH analysis for one single SFC station (considering ramp-up)

The impact of DSR on PV plants or any sun-based GPS mitigates their negative impacts and restore their competitiveness compared to other renewable energy (*Figure 26*). The DSR will allow ground operators to leverage their existing CAPEX by producing up to +60% incremental energy without making additional investment in infrastructure. The environmental impact of light pollution must be further assessed during the sub-scale demonstrator phase.

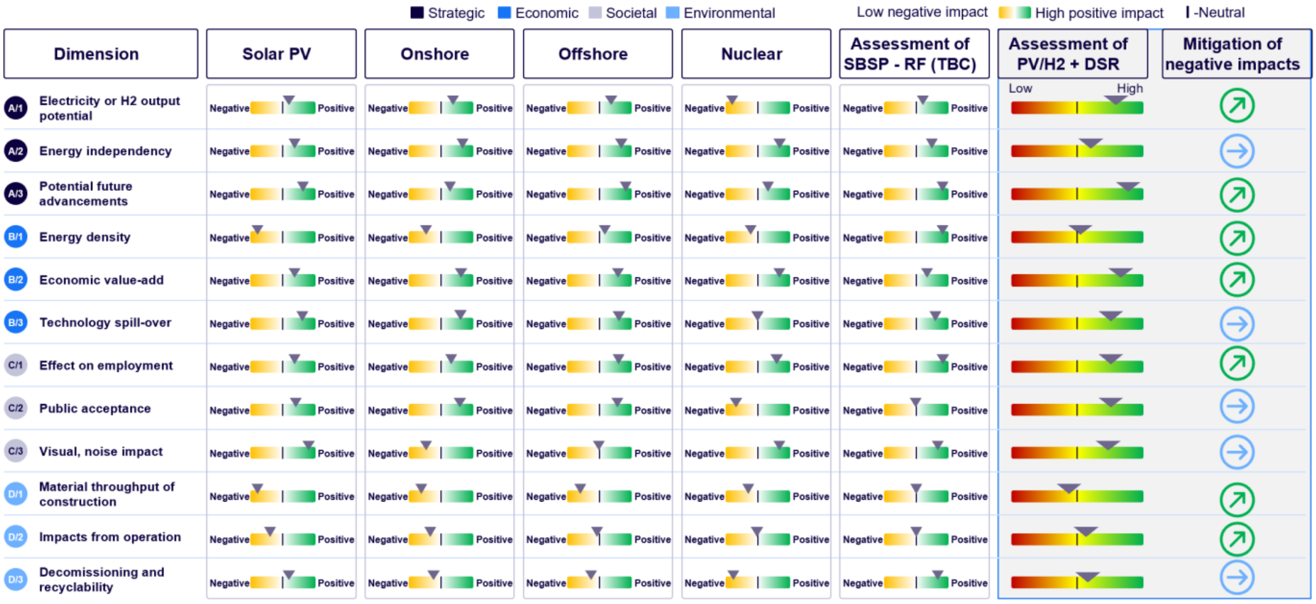


Figure 26 - Mitigation of negative impacts of PV plants thanks to DSR

9.3 GROUND STATION LOCATION

<u>SUB-SECTION KEY MESSAGES</u>

- Based on the SRS architecture, the objective is to illuminate the maximum of ground stations to provide enough energy
- The selection of the orbit trajectory is based on 20 identified priorities sites.
- We have assessed three main orbit trajectory scenarios to fit with the maximum capacity and cover one or more ENGIE plants and the reference trajectory covers six main sites, including one from Engie and major large PV plants where our concept is the most valuable.
- The trajectory seems compatible with no more than 30 sites, and a rough estimation of the theoretical number of ground stations to be covered demonstrates the impact of the 4000km of distance between plants.
- On pre-identified sites, more than 66% of the modelled power production of mirrors allow additional 2x 2h/d of irradiation 1'000W/m².
- In addition to existing plants, the objective is to build additional facilities to complete the production volume and leverage the Space segment with two configurations.

To optimize the utilization of the DSR architecture and maximize the energy production, the objective is to illuminate the maximum possible number of ground stations. The identification of the largest PV sites in the world, including their location, surface area and installed capacity, has allowed then to select the best orbit track to cover the maximum number of plants on the ground. Based on the chosen orbit track and DSR constraints, the maximum number of GPS that could be deployed has been estimated. Finally, the need for additional new GPS has been designed to complement the energy production.

9.3.1 IDENTIFICATION OF PRIORITY SITES

Priority sites have been identified based on four main criteria:

- **Type of technology –** Sites equipped with PV technology have been firstly selected. Offshore wind farms have also been included in the analysis because offshore solar panels could be a promising technology that could be implemented close to wind farm which have already been granted a permit. On top of that, Engie PV projects have been prioritized because, as part of the consortium, the implementation would be facilitated, and their sites are equipped with tracker technology allowing an increased production efficiency.
- **Surface area –** Sites with a surface area larger than 50 km^2 have been selected to have enough surface to receive the 8 km diameter spotlight from DSR. Exception is made for Engie sites since they are the top priority.
- **Installed capacity –** Sites with a production capacity above 2.5 GW have been selected. Exception is made for Engie sites since they are the top priority.
- **Location -** Sites in Europe or located in countries with good political and economic relations have been preferred. Sites in China or North Korea have been excluded of the analysis.

Filtering the data based on these criteria, 20 sites have been identified (*Table 16)*:

- 4 Engie sites, 12 other PV sites and 4 offshore wind farms
- Surface areas are ranging from 50 to 960 km^2, except for Engie sites which are smaller between 4 and 7 $km^{2.}$
- Installed capacities for PV sites are ranging from 4,500 to 20,000 MW, except for Engie sites which have a production capacity of 180 to 350 MW and offshore wind farms of 500 to 900 MW.
- Sites identified are in Europe (Spain, France, Netherlands, Denmark, Germany), America (USA, Mexico, Chile, Brazil), Asia (India, Indonesia, Oman) and Africa (Morrocco, Algeria, Egypt) and Oceania (Australia).

Type of site	Project	Location	Capacity (MW)	Area (km²)
ENGIE	Sun Valley 1*		347	7
ENGIE	Nueva Xcala*		200	4
ENGIE	Coya*		181	4
ENGIE	ANSON solar*		261	5
PV site	Powell Creek solar farm		20,000	120
PV site	Al Wusta Solar Plant		12,500	960
PV site	Ladakh Solar Park		10,000	n/a
PV site	HyDeal España solar farm		9,500	>50
PV site	Morocco-UK Solar Power		7,000	200
PV site	Berço Das Gerais Solar Park		5,700	80

*ENGIE *stations equipped with tracker technology*

Type of site	Project	Location	Capacity (MW)	Area (km²)
PV site	Riau Islands solar farm		4,800	30
PV site	Fortescue Green Hydrogen solar farm		4,600	n/a
PV site	Zaragoza and Teruel solar farm		2,580	n/a
PV site	Tafouk1 solar farm		4000	64
PV site	Total Eren-Guelmim-Oued Noun Solar		5000	1700
PV site	ArcellorMittal solar park		4500	n/a
OWF	Borssele 3&4		732	146
OWF	Kriegers Flak		605	132
OWF	Fécamp		497	78
OWF	Borkum Riffgrund 3		913	75

European sites

Table 16 - Identified priority sites for the orbit trajectory

9.3.2 SELECTION OF THE OPTIMAL ORBIT TRACK

An assessment of three main orbit tracks scenario has been conducted to cover at least on Engie site and fit the maximum capacity.:

- **Scenario 1** – Engie PV sites in the USA (Sun Valley 1 & ANSON solar) are selected as references to define the orbit trajectory.
- **Scenario 2 –** Engie PV site in Mexico (Nueva Xcala) is selected as a reference to define the orbit trajectory.
- **Scenario 3 –** Engie PV site in Chile (Coya) ais selected as a reference to define the orbit trajectory.

Scenario 3 seems to be the most promising one because it allows to cover the Chile site located on the descent meridian *(Figure 27)* and five other PV plants in the world *(Table 17).*

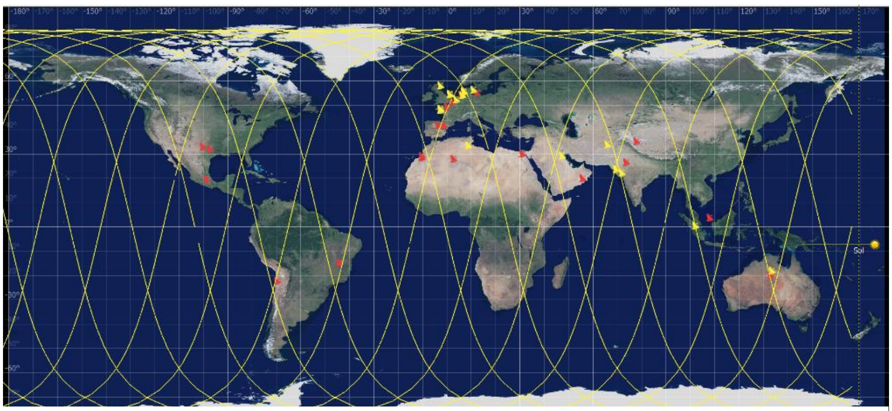


Figure 27 - Targeted orbit track

Site	Country	Production capacity	Energy generated	Surace area	Station type
		MW	MW	km^2	
Coya (ENGIE)	Chile	181	181	4	Small PV + ELY
Powell Creek	Australia	20,000	13,457	120	Large PV + ELY
Kutch (NTPC) Solar Park	India	4,750	4,750	40	Large PV + ELY
Dholera Solar Park	India	4,000	4,000	86	Large PV + ELY
Hydeal Espana Solar Farm	Spain	9,500	7,600	50	Large PV + ELY
Riau Solar & Storage	Indonesia	3,500	2,800	40	Large PV + ELY
TOTAL		**41,931**	**32,788**	**340**	

Table 17 - Sites covered by reference orbit track.

In addition to these six existing plants, it has been estimated that at least two small PV stations, not pre-listed, could be identified and be located on the selected orbit track. In addition to these plants, deployment of new plants under this track will also be key to generate the energy outputs required by ESA and lead to the profitability of the DSR architecture.

9.3.3 ESTIMATION OF THE MAXIMUM NUMBER OF DEPLOYABLE GPS

The main limiting constraint to the GPS deployment is the minimum required distance between two sites of 4,000km, which gives the time of the SRS constellation to change their mirror orientation to point at another GPS. Based on this assumption a maximum number of deployable sites of 35 GPS has been estimated as detailed in *Table 18.*

	Unit	Value	Comment
Earth circumference	km	44,000	
Minimum distance between 2 GPS on a meridian	km	4,000	Constraint defined by Thales Alenia Space
Maximum number plants on one meridian	#	11	
Maximum number of plants to be covered on Earth	#	154	The orbit track counts 14 meridians
Maximum number of sites on Earth	#	51	% earth vs deep sea = 33% (earth + coast until 50km for GPS in offshore wind areas)
Maximum number of sites on Earth (including limitations)	#	**35**	**30% of stations excluded because located in Russia or China**

Table 18 - Estimation of the maximum number of deployable GPS

The minimum distance of 4,000 km has a huge impact on the theoretical number of ground stations to be covered as illustrated in the

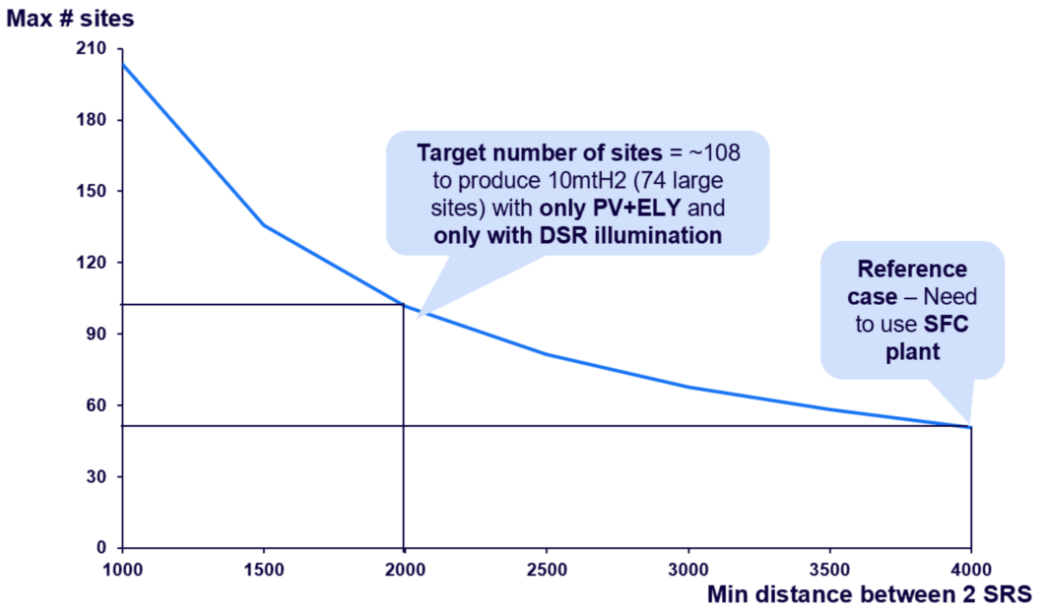


Figure 28. If the illumination is only provided by DSR and only PV with electrolysis technology is used, around 108 GPS, each one separated by minimum 2,000 km from another one, would be needed to meet the ESA requirement of 10m tons of hydrogen produced. With the 4,000 km constraint, the SFC technology must be used to increase energy production efficiency.

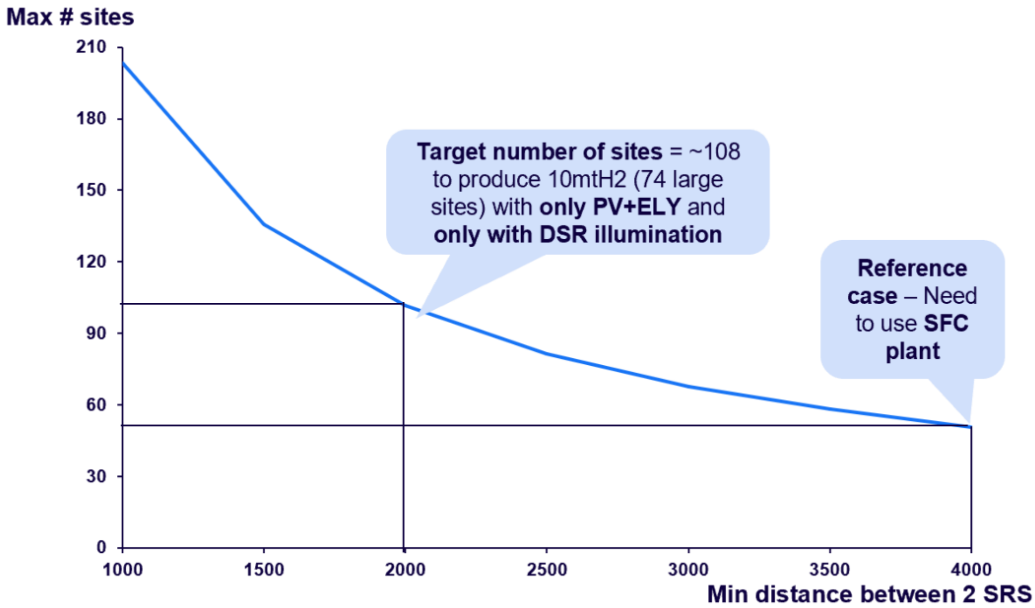


Figure 28 - Maximum number of GPS based on minimum distance allowed by SRS constellation

9.3.4 DESIGN OF THE ADDITIONAL GPS NEED

As the size of Europe (5,000km x 4,000km) allows very limited deployment of potential sites compliant with the minimum inter-distance of 4000km described above, any additional plants should be located outside Europe. Large GPS producing H_2 (PV+ELY and SFC) are preferred to maximize the H_2 production. SFC technology has a higher efficiency ratio but is still in development and its deployment is expected to start from 2040, while PV+ELY stations will be available early from 2035. These new plants should also be ideally located in areas with the maximum of clear-sky index and not too far from Europe. Equatorial GPS are expected to receive 4 hours of DSR illumination per day (two flights of the DSR constellation) while non-equatorial only 3 hours (one flight and a half of the DSR constellation)

	Unit	Large Equatorial	Large Non-Equatorial	TOTAL
PV+ELY	#	5	5	**10**
SFC	#	5	7	**12**
TOTAL	#	**10**	**12**	**22**

Table 19 - Number of new GPS to deploy for increasing outputs

Considering the existing and new plants, DSR is estimated to deliver energy to 30 GPS, split between the type of technology (PV, PV+ELY, SFC), existing / new and location (equatorial/non-equatorial).

	Unit	Large GPS		Small GPS		TOTAL
		Existing	New	Existing	New	

PV	#	-	-	2	-	**2**
PV+ELY	#	5	10	1	-	**16**
SFC	#	-	12	-	-	**12**
TOTAL	#	**5**	**22**	**3**	**-**	**30**

Table 20 - Ground segment configuration

10. CONFIRMATION OF THE BUSINESS CASE

SECTION KEY MESSAGES

- In terms of business model, we have designed the Space segment as it will be managed “separately” from the ground segment.
- Each scenario has been modelized with two scopes of the SBSP added value.

10.1 DSR VALUE CHAIN AND VALUE PROPOSITION

The business model of the DSR is designed in two segments: Space only and new infrastructure. To this study, Space only and the Consolidated views (Space + New Infrastructure) will be compared. The DSR value chain is illustrated in the *Figure 29*

10.1.1 SPACE ONLY VIEW

Considering the Space only (hereafter designed as SpaceCo) view, SpaceCo revenues come from the sale of energy generated from incremental illumination provided by DSR at dawn and/or dusk to existing and new GPS, based on a defined transfer price. CAPEX is composed of the SRS construction costs and launching costs, including launching for maintenance purpose. OPEX include the costs of running space operations and the replacement of mirrors.
The environmental impact can be assessed by computing the amount of energy required and CO_2 emitted for the deployment of the space infrastructure only, compared with the energy generated and CO2 avoided along the lifetime of the infrastructure.

10.1.2 CONSOLIDATED VIEW

Considering the Consolidated view, revenues come from the sale of energy generated from incremental illumination provided by DSR at dawn and/or dusk to existing and new GPS, to which is added the revenues from the sale of energy generated from natural illumination on new GPS. CAPEX is composed of the SRS construction costs and launching costs, including launching for maintenance purpose, costs of building new GPS and costs for the replacement of the stacks of electrolysis. OPEX include the costs of running space operations, the replacement of mirrors and the operating & maintenance costs of GPS. CAPEX and OPEX for new infrastructure vary depending on the type of stations deployed.
The environmental impact can be assessed by computing the amount of energy required and CO_2 emitted for the deployment of the space infrastructure and the building of new facilities and their exploitation.

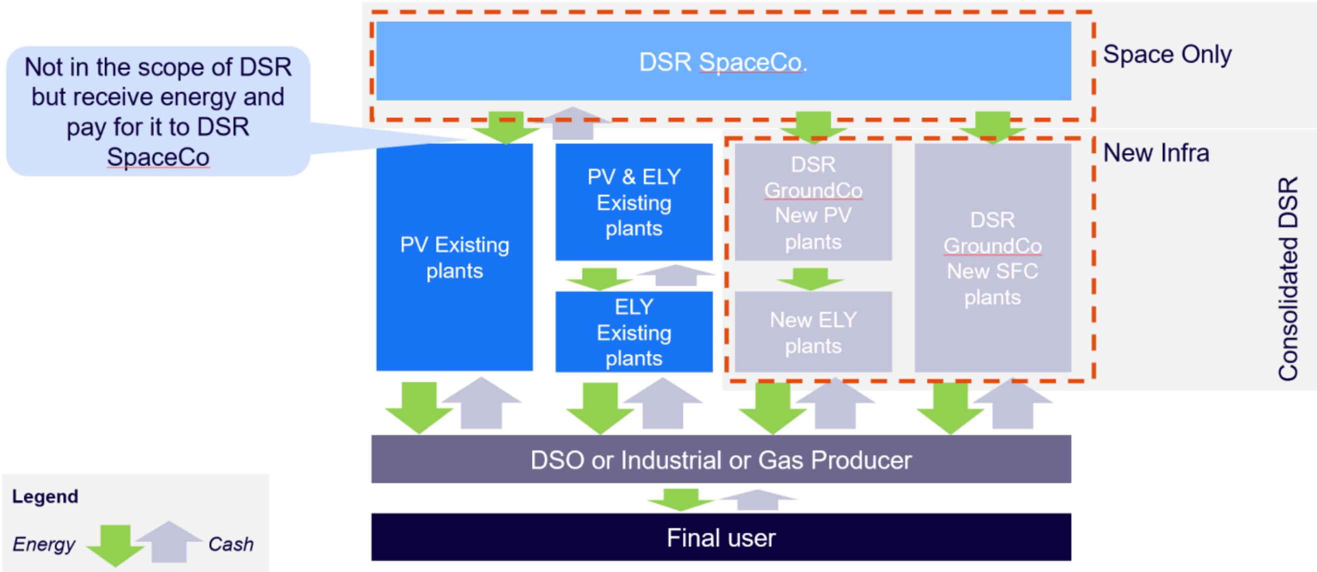


Figure 29 - DSR value chain

10.2 PRESENTATION OF 4 BUSINESS CASES

SUB-SECTION KEY MESSAGES

- All DSR scenarios offer competitive LCOH for the next decades. SFC helps to increase the production volume.
- An architecture including ground facilities is competitive and fits with the ESA requirements thanks to SFC technology.
- Working only with PV stations generating electricity offers a competitive LCOE but supposes energy storage, as large stations exceed 1GW, power not compliant with system constraints.
- An architecture only based on electrolysis technology offers a competitive LCOH and just enough production volume requested by ESA.
- The new “SFC stations only” scenario shows interesting LCOH and H2 production but is still a technology in development and stations can only be deployed from 2040.

4 business cases have been identified. The number of new GPS to be deployed changes depending on the scenario analyzed:

- The reference scenario assumes 10 new PV+ELY and 12 new SFC GPS
- The PV only scenario assumes 22 new PV GPS
- The PV+ELY only scenario assumes 22 new PV+ELY GPS
- The SFC only scenario assumes 22 new SFC GPS

For all 4 scenarios, the number of existing GPS however remains the same: 8 existing GPS split between 2 small PV, 5 large PV+ELY and 1 small PV+ELY. The results of the comparison are summarized in the *Figure 31* and *Figure 30.*

10.2.1 REFERENCE SCENARIO

a. Consolidated

In the consolidated reference scenario, a mix between PV + ELY and SFC stations has been made: 10 large new PV + ELY stations are projected to be deploy from 2035 and 12 SFC stations from 2040. This configuration shows competitive LCOH (1.8 €/kg H_2 consolidated), profitability (consolidated NPV of €57bn) and fits with the ESA requirements thanks to SFC technology (18m tons of hydrogen produced at project peak).

b. Space only

At the difference of the consolidated scenario, the space only reference scenario does not take into account the CAPEX and OPEX allocated to the ground segment (essentially building of GPS and operation & maintenance costs). Since no investment is made in the ground infrastructure, only the incremental energy provided by the DSR to the 22 new GPS is considered (in addition to energy provided to existing GPS). It allows to have a best in-class EROI but does not meet the energy production requirement of the ESA (only 6m tons of hydrogen produced per year at full operation).

10.2.2 PV ONLY SCENARIO

In the PV only scenario, 22 large new PV stations are deployed from 2035 for 30 years. Working only with PV stations generating electricity offers a competitive LCOE of 22 €/MWh (consolidated, vs 43 €/MWh for the reference scenario) because of a low PV unit CAPEX compared to other technologies (320€/kWp). However, this configuration does not allow to reach any ESA requirement in terms of energy production: at full scale operation, per year, only 718 TWh of electricity are produced (vs. 750 TWh per year required by ESA) and 0.6m tons of hydrogen (produced by the 5 PV+ELY GPS, vs. 10m tons per year required by ESA). It also supposes additional energy storage, as large stations exceeding 1GW are not compliant with system constraints.

10.2.3 PV + ELY ONLY SCENARIO

In the PV+ELY only scenario, 22 large new PV + ELY stations are deployed from 2035 to 2064. An architecture only based on electrolysis technology offers a competitive LCOH of 2.4 €/kg H_2 (consolidated) below the transfer price from H_2 operator to end-user of 2.5 €/kg H_2. Yet, 22 new PV + ELY generate just enough production volume requested by ESA. Regarding, the financial performance, the NPV consolidated is low (€9bn) due to high unitary CAPEX to build a PV + ELY station (700 €/kWp), on top of which must be added costs for the replacement of the stacks occurring every 7 years and costing 53 €/kWp (14% of CAPEX).

10.2.4 SFC ONLY SCENARIO

In the SFC only scenario, 22 new large SFC stations are deployed from 2040 to 2069. This scenario is the most promising with interesting LCOH (1.5 €/kg H_2 consolidated) and high hydrogen production volume due to a good energy production efficiency (40%): 715m tons of hydrogen could be produced over 30-year-lifetime and up to 25m tons per year at project peak, far exceeding ESA requirements. However, SFC is still a technology in early-stage development and GPS are only projected to be deployed from 2040.

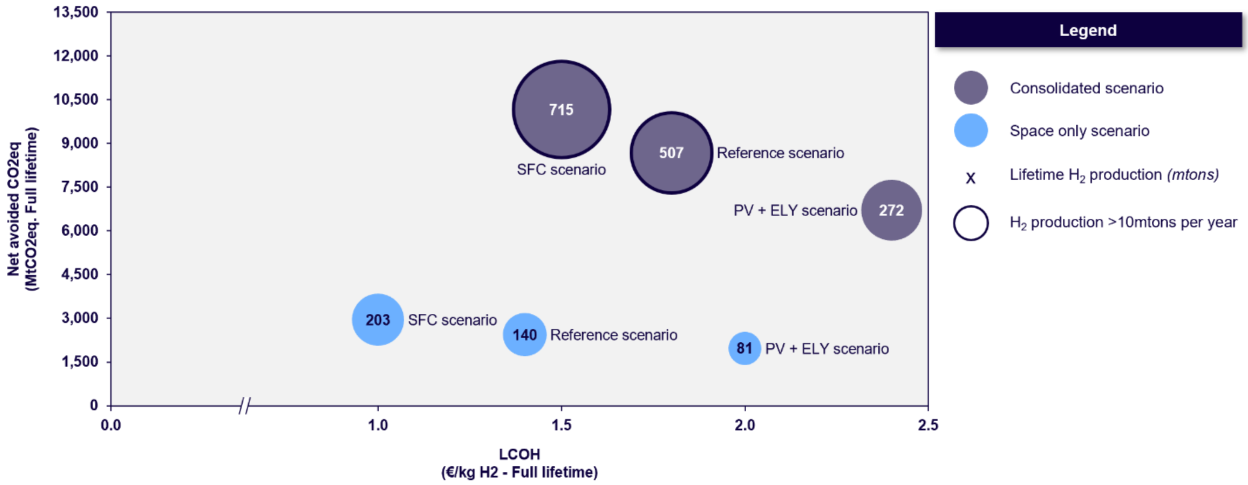


Figure 30 - Positioning of the different architecture scenarios

		Reference Consolidated	Reference Space only[1]	PV only	PV + ELY only	SFC only
Ground power stations	**Number of large GS** *Existing / New PV / ELY / SFC*	**5 / - / 10 / 12**	**5 / - / 10 / 12**	5 / 22 / - / -	5 / 0 / 22 / 0	5 / - / - / 22
	Number of small GS *Existing / New PV / ELY / SFC*	**3 / - / - / -**	**3 / - / - / -**	3 / - / - / -	3 / - / - / -	3 / - / - / -
Financial performance	**Total conso / space costs** *(bn€, non-discounted)*	**355 / 73**		164 / 73	292 / 73	408 / 73
	LCOH conso / space only *(€/kg H2)*	**1.8 / 1.4**		28 / 10.4	2.4 / 2.0	1.5 / 1.0
	NPV conso / space only *(bn€, discounted)*	**60 / 8**		384 / 39	12 / 9	176 / 23
Energy performance	**Electricity produced** *(TWh, for 30 years)*	**22**	**22**	15,569	22	22
	Energy prod. for H2 / H2 vol. *(TWh H2 / mtons H2, for 30 years)*	**20,402 / 507**	**5,869 / 140**	795 / 13	16,342 / 272	24,173 / 715
	Max energy / H2 produced[2] *(TWh / mtons H2, per year)*	**718 / 18**	**234 / 6**	577 / 0.6	577 / 10	837 / 25
	EROI	**63**	**69**	49	49	72
Environmental	**Carbon intensity** *($kgCO_{2,eq}/MWh$)*	**4.1**	**14.4**	5.2	5.2	3.5
	Net lifetime avoided CO_2 *(MtCO2eq, for 30 years)*	**8,677**	**2,442**	6,935	6,935	10,147
	Energy produced per mass unit *(MWh/kg)*	**450**	**130**	360	360	533

Note: Values for 22 new GPS lifetime deployed from 2035 for PV + ELY stations and from 2040 for SFC stations with a lifetime of 30 years with a selected launch plan PROTEIN + additional Starship
1) In this scenario no investment are made in the ground segment ; 2) Volume of H2 produced at project peak after 2050

Figure 31 - Key indicator by architecture scenario

10.3 COST COMPETITIVENESS AND FINANCIAL PERFORMANCE

SUB-SECTION KEY MESSAGES

- New ground infrastructure TCO are ~4x higher than space TCO but allow to exceed the H2 production volume required by ESA (18 mtons per year)
- Considering the consolidated business plan, the project will be profitable from 2047.
- Considering the space only business plan, the project will be profitable from 2046

The space segment is composed of 3,987 SRS, 11.4 tons each, resulting in total mass to be launched of 45,404 tons. Over the project lifetime, 1,691 launches are required to send the initial SRS in space and the replacement mirrors *(see 6.1.2)*. The ground segment includes the building and operation of the 22 new GPS, which is highly expensive: TCO of new infrastructure only is around four times higher than the TCO of Space only *(Figure 32* and *Figure 33)* mainly due to high construction CAPEX accounting for 75% of total new infrastructure TCO. The ESA requirements in terms of hydrogen production can only be reached with the investment in new ground infrastructure: with the 8 existing and 22 new GPS, 18m tons of hydrogen can be produced per year at full-scale operation.

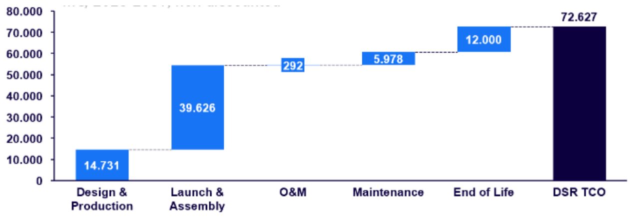


Figure 32 - TCO Space only 2025-2081(m€, non-discounted)

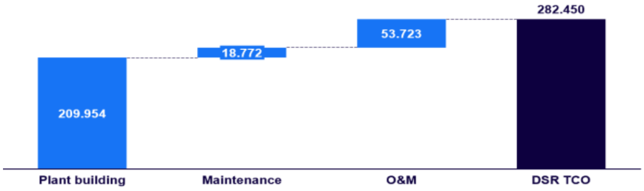


Figure 33 - TCO New ground infrastructure only 2025-2081 (m€, non-discounted)

From a consolidated view *(Figure 34),* the project is expected to generate revenues of approximately €1,270bn over its lifetime. CAPEX is the highest cost item (ca. €280bn), due to the construction of SRS, the building of new PV + ELY and SFC between 2030 and 2045 and the stacks replacement of the electrolysis every 7 year. Over its lifetime, the project is expected to provide ca. €910bn of operational cash flow (non-discounted). Even with major ground investments, the DSR project can be break-even 15 years after its first launch.

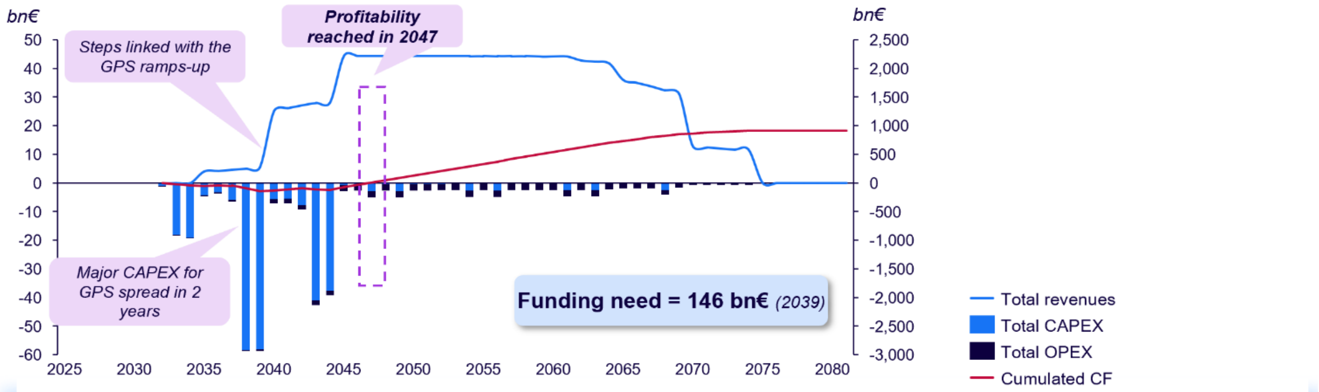


Figure 34 - Consolidated financial performance analysis (non-discounted)

From a space only view *(Figure* 35*),* the project is expected to generate revenues of ca. €236bn over its lifetime. Total CAPEX for SRS construction amount ca. 55 bn€ and total OPEX for running space operations ca. €18bn. Over its lifetime, the project (space only) is expected to provide ca. €164bn of cash flow (non-discounted); The funding needs for the Space Only model is 28 bn€ in 2041, but the break-even is reached six years after.

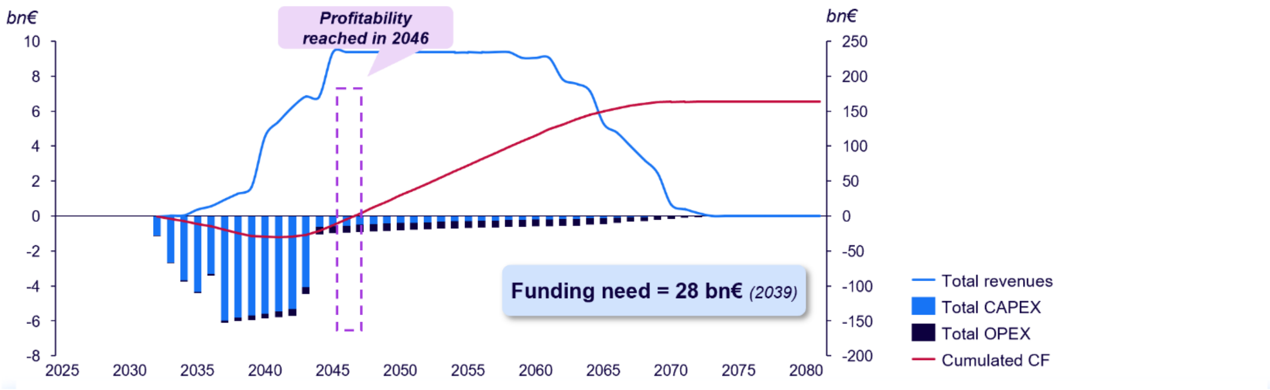


Figure 35 - Space only financial performance analysis (non-discounted)

10.4 ENVIRONMENTAL PERFORMANCE

The project has also an environmental dimension, and it is essential that it has a positive environmental impact in terms of energy production and CO_2 emissions avoided.

10.4.1 ENERGY ROI

SUB-SECTION KEY MESSAGES

- In the consolidated reference scenario, DSR will reach energy neutrality as of 2035.
- In the space only reference scenario, DSR will reach energy neutrality as of 2036.

In the consolidated reference scenario, ca. 20,430 TWh are produced over the project lifetime while ca. 330 TWh of energy are required for launches, satellites' production, and new stations deployment, which makes a cumulated positive energy footprint of ca. 20,100 TWh and energy neutrality is reached as of 2035 *(Figure 36).* Building of new ground infrastructure spends a lot of energy but their impact is quickly offset by their high energy production.

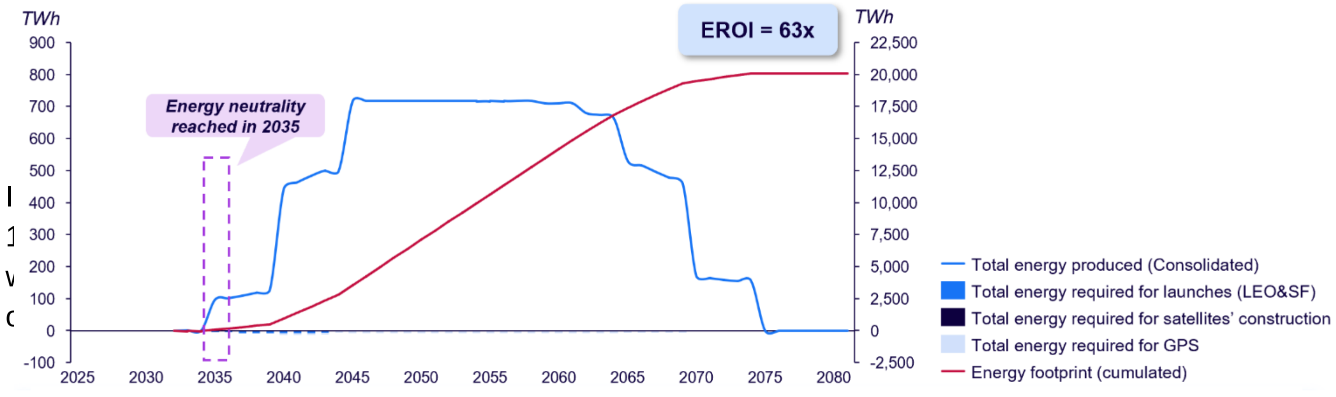


Figure 36 - Consolidated energy production and consumption (non-discounted)

In the space only reference scenario, ca. 5,900 TWh are produced over the project lifetime while ca. 90 TWh of energy are required for launches and satellites' production, which makes a cumulated positive energy footprint of 5,810 TWh and energy neutrality is reached as of 2035 *(Figure 37).*

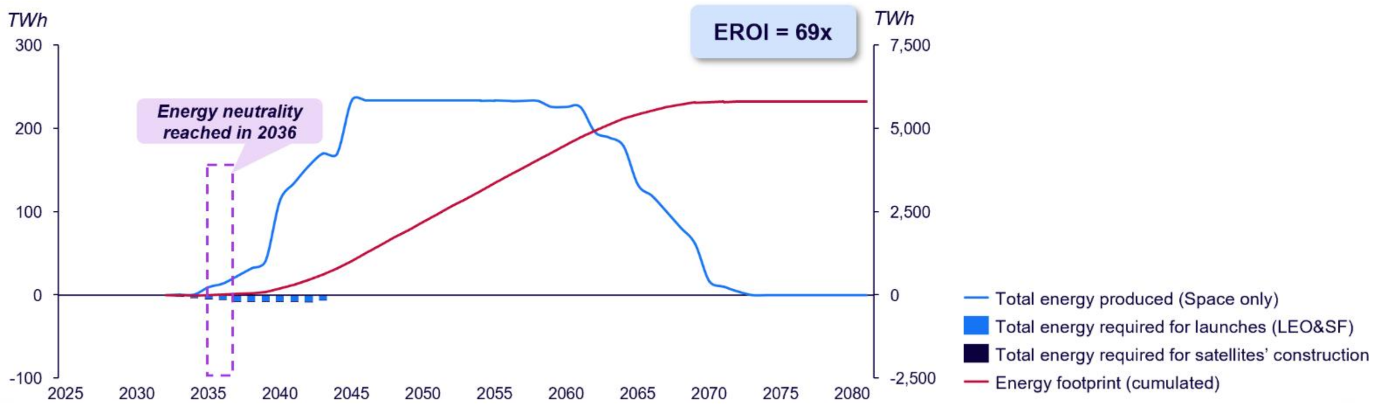


Figure 37 - Space only energy production and consumption (non-discounted)

10.4.2 CARBON FOOTPRINT

SUB-SECTION KEY MESSAGES

- Considering the consolidated avoided CO2 emissions, DSR allows to avoid up to 300 million tons of CO2 per year at full scale deployment.
- Considering the avoided CO2 emissions by space only, DSR allows to avoid up to 100 million tons of CO2 per year.

Launching phase has the highest carbon footprint with ca. 85m tons CO2 emitted over the project lifetime.
In the consolidated reference scenario, the project is expected to produce ca. 20,430 TWh of energy on its lifetime, corresponding to ca. 8.8 bn tons of CO_2 avoided. Deducting the CO_2 emitted for launch and satellite construction, the net avoided CO_2 is ca. 8.7 bn tons. Carbon neutrality is reached in 2035 (*Figure* 38*)*.

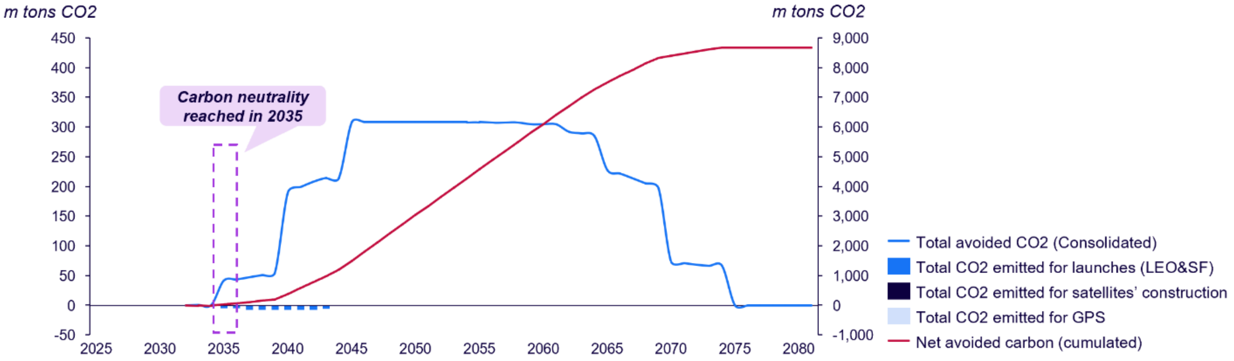


Figure 38 - Consolidated carbon avoided and emitted (non-discounted)

In the space only reference scenario, the project is expected to produce ca. 5,900 TWh of energy on its lifetime, corresponding to 2.5 bn tons of CO2 avoided. Deducting the CO_2 emitted for launch and satellite construction, the net avoided CO_2 is ca. 2.4 bn tons. Carbon neutrality is reached in 2039 *(Figure* 39*)*.

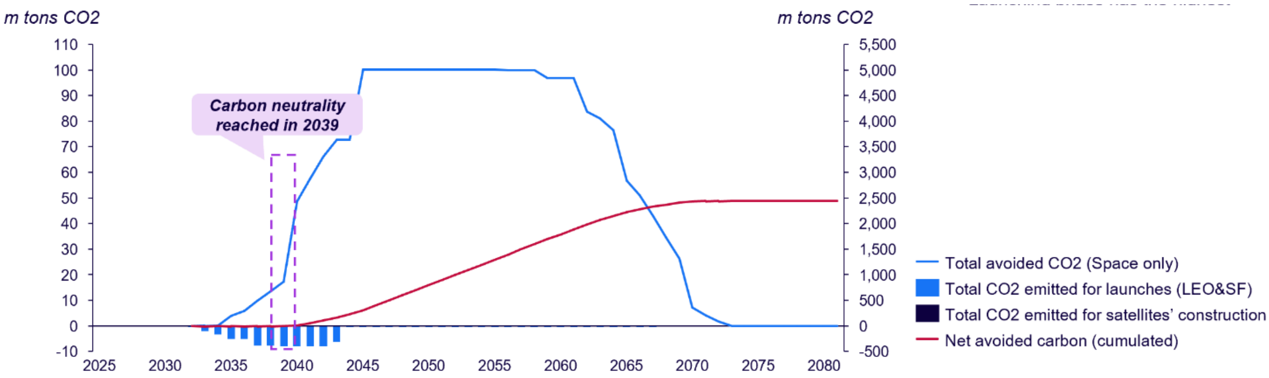


Figure 39 - Space only carbon avoided and emitted (non-discounted)

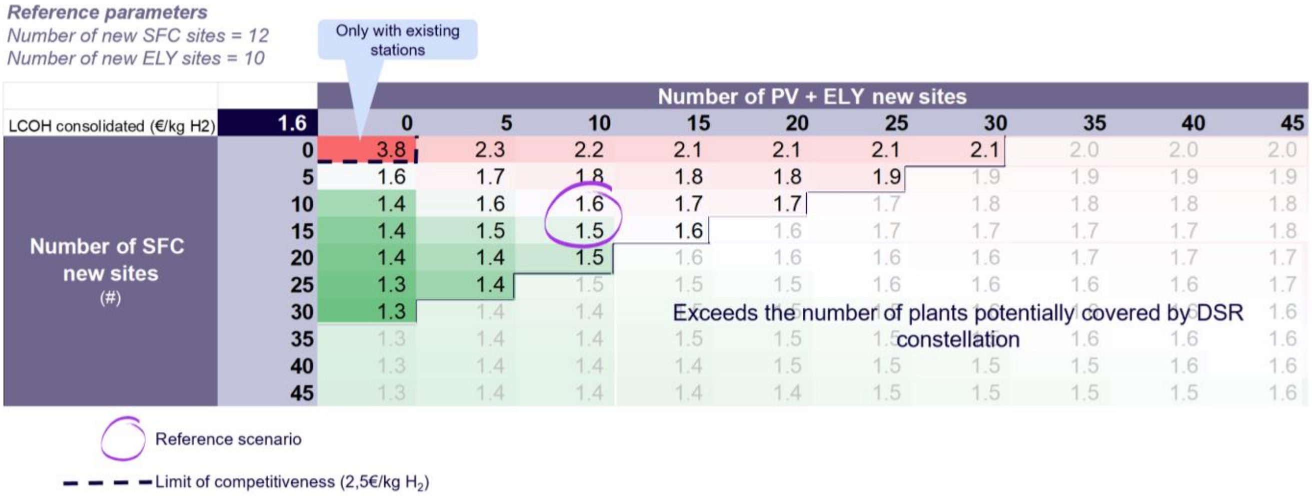
10.5 SENSITIVITY ANAYSIS & ASSUMPTIONS

SUB-SECTION KEY MESSAGES

- LCOH consolidated is minimized when more SFC stations are deployed. A minimum of SFC plants are required to get a competitive H2 price in the future.
- The WACC for the consolidated reference scenario has a significant impact on LCOH whatever the number of new sites deployed.
- The most impactful parameters on consolidated LCOH are mirror diameter, reflection coefficient, SFC efficiency ratio and consolidated WACC.
- It is pretty similar for H_2 production, except that we also add the filling ratio, installed capacity and energy delivered post SFC.
- Considering the consolidated scenario, the DSR system appears to be resilient even in the worst scenario.

10.5.1 SENSITIVITY ANALYSIS ON CONSOLIDATED LCOH

LCOH is a key indicator of the DSR system performance and to be competitive, it must be below the hydrogen selling price to end-users of 2.5 €/kg H_2. A first sensitivity analysis on the consolidated LCOH was performed based on the mix between the number of new GPS by type (PV + ELY and SFC). Except when no new GPS are built, the LCOH is always below 2.5 €/kg H_2 *(Figure 40).* LCOH consolidated is also minimized when more SFC stations are deployed, therefore, a minimum of SFC plants is required to get a competitive H_2 price on the longer-term.



LCOH consolidated (€/kg H2)	1.6	Number of PV + ELY new sites									
		0	5	10	15	20	25	30	35	40	45
Number of SFC new sites (#)	0	3.8	2.3	2.2	2.1	2.1	2.1	2.1	2.0	2.0	2.0
	5	1.6	1.7	1.8	1.8	1.8	1.9	1.9	1.9	1.9	1.9
	10	1.4	1.6	1.6	1.7	1.7	1.7	1.8	1.8	1.8	1.8
	15	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.7	1.8
	20	1.4	1.4	1.5	1.6	1.6	1.6	1.6	1.7	1.7	1.7
	25	1.3	1.4	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.7
	30	1.3	1.4	1.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.6
	35	1.3	1.4	1.4	1.5	1.5	[illegible]	[illegible]	1.6	1.6	1.6
	40	1.3	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.6	1.6
	45	1.3	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.6

Figure 40 - Sensitivity on consolidated LCOH based on the mix of new GPS

The second sensitivity analysis on the consolidated LCOH is based on the WACC which is a financial metric used to determine the discount rate for evaluating the present value of future cash flows and making investment decisions. The WACC consolidated has a significant impact on LCOH consolidated in the reference scenario whatever the number of new sites deployed *(Figure 41)*: it can range from 1.5 €/kg H_2 at a 7% WACC to 2.5 €/kg H_2 (+65%) at 13% WACC.

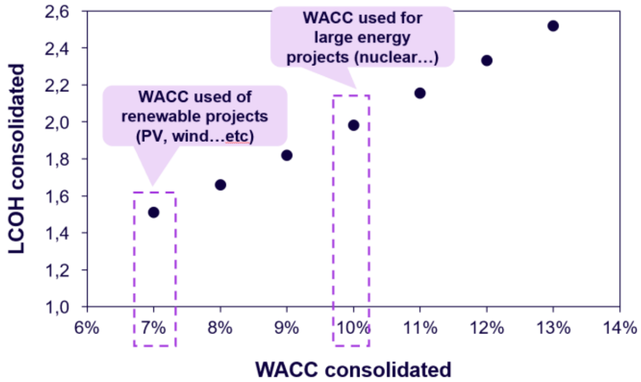


Figure 41 - Sensitivity analysis of LCOH consolidated based on WACC consolidated

Different WACC values have been selected for modelling depending on the technology used and the associated risk and are detailed in the sub-section *7.5.2*.

Sensitivity analysis on the consolidated LCOH has also been performed based on defined space and ground segment parameters *(Figure 42* and *Figure 43)*. Regarding the space segment, the three parameters with the highest impact on the consolidated LCOH are the orbit altitude (which is defined at 890 km and cannot be changed), the mirror diameter and the reflection coefficient: if the reflection coefficient is increased by 10%, the consolidated LCOH decreases by 4.5%. Considering the ground segment, top three most impactful parameters are the WACC consolidated, the SFC efficiency ratio and the energy delivered post SFC by natural illumination. The same analysis has been conducted on the volume of hydrogen produced in the reference consolidated scenario. Top three parameters remain unchanged for the space segment. Regarding the ground segment, the filling ratio, SFC efficiency ratio and the installed capacity for large GPS have the most significant impact on the hydrogen production. For instance, if the filling ratio of the GPS is increased by 10%, the volume of hydrogen produced is also increased by 10%.
This analysis helped determine which parameters could be adjusted in priority to decrease the LCOH or increase the volume of hydrogen produced.

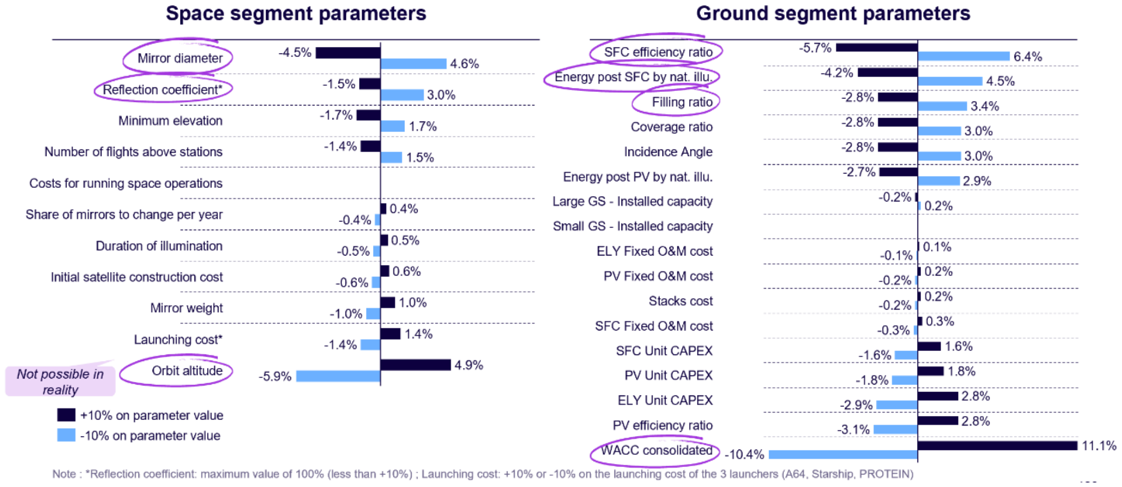


Figure 42 - Sensitivity analysis on the consolidated LCOH

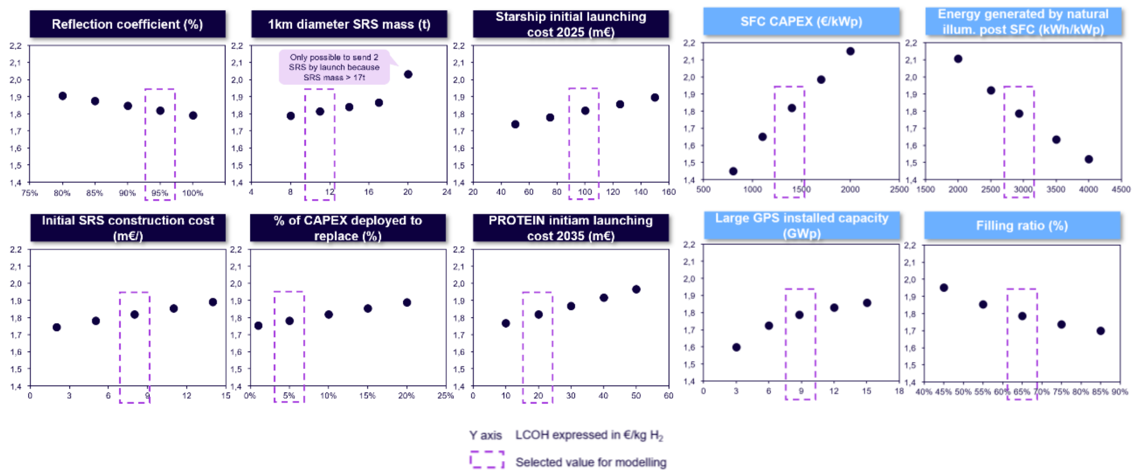


Figure 43 - Sensitiviy analysis on the consolidated LCOH for most impactful parameters

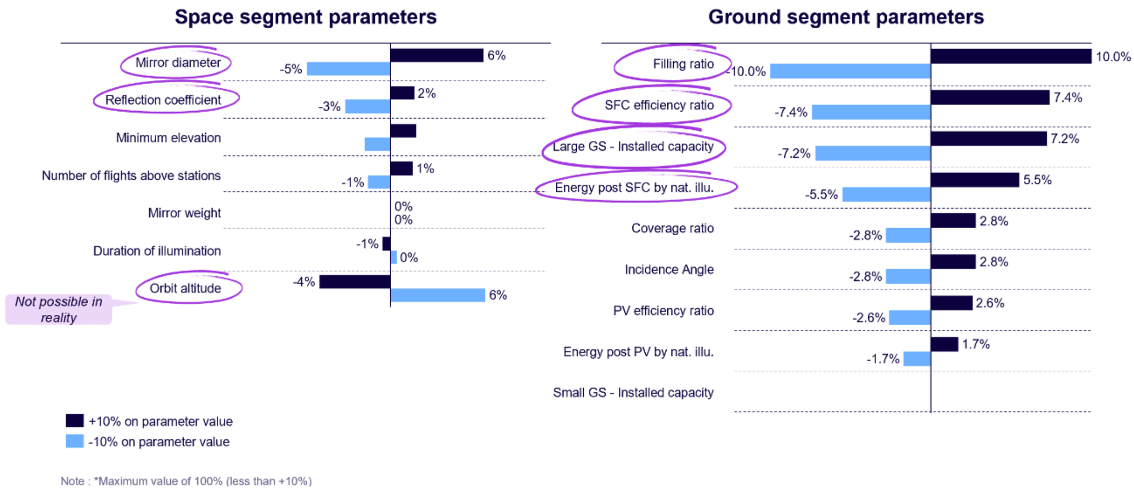


Figure 44 - Sensitivity analysis on the volume of hydrogen produced

10.5.2 ASSUMPTIONS AND RATIONALE

This sub-section is dedicated to explaining the rationale behind the most impactful parameters assumptions.

- **Orbit altitude**

This parameter has been set at 890 km by previous studies and cannot be changed

- **Mirror diameter**

This parameter has been estimated by previous studies at 1 km diameter, which has been defined as the optimum SRS size to be able to deliver enough energy while limiting the number of SRS to be sent in space.

- **Reflection coefficient**

The reflection coefficient takes into consideration the energy loss of the illumination due to imperfect reflection and pointing errors. NASA studies were conducted on the basis of a maximum rms gradient of 0.00082 rad, corresponding to an edge gradient of 0.001 rad for a spherically curved circular membrane. This corresponds to an energy loss of 18% of the illumination, which seems reasonable when compared to other losses due to imperfect reflection and pointing errors. Solspace project assumed a 92% reflection coefficient following earlier studies (Canady and Allen, 1982). 95% has been selected considering that in the next decade improvement on this topic especially new materials and management of large surface will allow to reach this coefficient.

- **WACC**

Four WACC have been used for modelling:

- A WACC Space of 10% was considered for this project because it is a large-scale project with a high level of risk, that can though be slightly mitigated by public investments.
- The WACC PV + ELY was estimated based on a study conducted by the International Energy Agency, which has taken a WACC of 7% to compute the LCOE of solar PV.
- The WACC SFC was estimated based on a feasibility study for a small reactor module conducted by the UK National Nuclear Laboratory that estimates a WACC of 9%.
- A WACC consolidated of 9% was considered for this project because it is a large-scale project with a high level of risk, particularly due to the space segment. Yet, the risk is mitigated by public investments, and lower risk profile investment for ground stations (WACC of 7%).

- **SFC efficiency ratio**

The yield rate of SFC technology can be measured in terms of energy conversion efficiency, which is the percentage of solar energy that is successfully converted into chemical fuel. SFC technologies are still in development and its efficiency is today lower than other technologies (10% for SFC vs 27% for PV). Yet, SFC appears more promising for H2 production without the intermediate production of electricity and many actors are working on this technology to improve its efficiency. The efficiency of most investigated thermochemical cycles is expected to range between 40–50%. The assumption of 40% has been taken for modelling.

- **Energy delivered post SFC by natural illumination**

Energy generated by natural illumination post PV is estimated at 1,977 kWh/kWp for a PV to electricity efficiency ratio of 27% and determined from the average of sun yields values of a baseline site configuration by Engie (nine pre-identified locations, excluding European and non-equatorial sites). SFC has a higher efficiency ratio compared to PV : it is estimated at 40%. Energy generated by natural illumination post SFC = 1,977 / PV efficiency ratio * SFC efficiency ratio = 2,929 kWh/kWp.

- **Installed capacity of large GPS**

Electric power has been computed for a large ground station with a surface of 50km2, compatible with the spot size generated by DSR. With this hypothesis, the 1,000 W/m2 emitted by DSR to earth provides a power after atmospheric attenuation of 50,265 MW. Following attenuation ratio have been considered in the computation of the electric power: coverage attenuation, filling rate, incidence angle and electricity conversion ratio. After attenuation, the electric power generated by a large ground station is 5,637 MW. Installed capacity is computed based on the electric power generated after atmospheric attenuation but before coverage and incidence angle to be able to accept the maximum of power in the ideal case. For large GPS, it is estimated at 8.8 GWp *(Table 21)*

	Real production		Installed capacity	
	Ratio (%)	**Power (GW)**	**Ratio (%)**	**Power (GW)**
Power after atm. attenuation		**50.3**		**50.3**
Power after coverage attenuation	*90%*	45.2	100%	50.3
Power after filling rate attenuation	*65%*	29.4	65%	32.7
Power after incidence angle attenuation	*71%*	20.9	100%	32.7
Electricity generated	*27%*	**5.6**	27%	**8.8**

Table 21 - Computation of the installed capacity for a large GPS (50 km²)

10.5.3 ASSUMPTIONS ON TRANSFER PRICES

Transfer prices are used to compute revenues based on the GPS operator energy production. Different transfer prices have been assumed for modelling depending on the situation considered and are summarized in the *Table 22.*

	Unit	Value	Application
SpaceCo to PV operator	€/MWh eq.*	80	To compute incremental revenues from existing and/or new GPS
SpaceCo to H_2 operator	€/MWh eq.*	40	
PV operator to electricity consumer (baseline)	€/MWh	110	To compute new PV stations revenues from natural illumination
PV operator to electricity consumer (peak hour)	€/MWh	150	To compute new PV stations revenues from DSR illumination at dawn and dusk
H_2 operator to end customer	€/kg H_2	2.5	To compute revenues of PV+ELY and SFC GPS

**SpaceCo will not directly sell to the customer of the operator, the price has been estimated based on the price of the energy that the operator could sell. But the real price will be based on the illumination provided by SpaceCo*

Table 22 – Transfer prices assumptions and applications

11. ASSESSMENTS OF SCALABILITY AND INDUSTRIAL CAPABILITY

SECTION KEY MESSAGES

- Ramp-up is a recurring pitfall for industrial development projects, with unrealistic timing and resources planned to reach full capacity at target performance and costs, mainly due to the design of the global project.
- The DSR design respects the two main criteria for a deployment success: replicable modularity and speed thanks to possibility of design iterations for SRS.
- The DSR architecture is composed of fully replicable modules and components, ensuring speed and reliability in the scale-up process.
- The launching capacity is the main bottleneck for deploying the DSR architecture as soon as possible.

11.1 CHALLENGES ON THE RAMP-UP PHASE

The ramp-up phase is a recurring pitfall for industrial development projects and must be well anticipated and managed to ensure the success of the project. From the analysis of industry examples, a few key takeaways have been identified.

- The number of steps in a process, although simple, is a direct driver of a process complexity and will require longer debottlenecking to reach target performance
- The higher the complexity of an operation, the longer it takes to fine-tune the developed equipment and the longer the knowledge transfer to labor
- Automation adds a great share of required time in ramping-up a process as it limits flexibility and adaptability
- It is often a good trade-off to start more manual and progressively set-up automations

Ramp-up failures are often due to unrealistic timing and resources planned to reach full capacity at target performance and costs or due to the design of the global project.

A successful scale-up is based on two key criteria: a replicability modular to create a feedback loop for test-learn-improve over the deployment period and a speedy delivery *(Figure 45).* Example of smart scale-up is the Tesla Giga Factory, which managed to start the production only three years after the construction start. Among ramp-up failures are included the Eurotunnel which operation start was delayed by 30% incurring 80% budget overruns *(Table 23).*

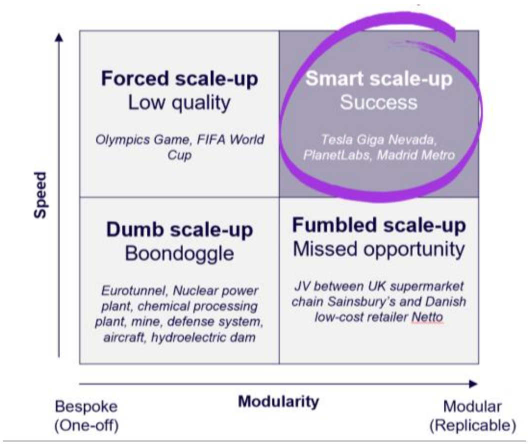


Figure 45 - Scale-up strategies segmentation

Projects	Sub-sector	Country	Construction start	Announced construction time	% construction time overruns	Announced budget	% budget overruns
Tesla Gigafactory 1	**Lithium battery**	USA	2014	3	-	5bn USD	-
London Array	**Offshore wind farm**	UK	2011	2	-	3bn USD	-
Madrid Metro	**Mobility**	Spain	1995	8	-	n.a.	n.a.
Olympic Games	**Sport event**	World					**+172% of overrun**
Eurotunnel	**Mobility**	UK	1988	6	**+30%**	n.a.	**+80% over construction budget +140% over financing**
Japan	**Nuclear Power Plant**	Monju	1986	9	**+230%**	12bn USD	**+25%**
Sanmen 1, 2		China	2009	5	**+80%**	2,044 USD / kWe	**+55%**
Vogtle 3, 4		USA	2013	4	**+125%**	4,300 USD / kWe	**+100%**
Shin Kori 3, 4		Korea	2008	5	**+100%**	1,828 USD / kWe	**+30%**
Olkiluoto 3		Finland	2005	5	**+220%**	2,020 USD / kWe	**+180%**
Flammanville 3		France	2007	5	**+200%**	1,886 USD / kWe	**+350%**
Taishan 1, 2		China	2009	4.5	**+100%**	1,960 USD / kWe	**+65%**
Novovoronezh II-1 & 2		Russia	2008	4	**+150%**	2,244 USD / kWe	n/a

Good practices: Tesla Gigafactory 1, London Array, Madrid Metro

Table 23 - Scale-up examples

11.2 DSR RAMP-UP

The DSR meets the conditions for a successful ramp-up. It has a modular architecture and replicable modules because the experience from delivering one module can be used to improve the delivery of the next, repeatedly, ensuring that the quality of delivery constantly improves. Replicability is also conducive to experimentation, from experiment to full scale when we master delivery. The speedy delivery, especially to deliver the Minimum Viable Product is linked to the simple, modular designs, quite easy and quick to build. After a first period of scale-up, the program becomes a matter of repeating the experience over and over, until the full-scale delivery. It is key to respect the First Law of Forecasting: "You have relative certainty for the first year of a forecast, and you can forget about knowing much about anything beyond three to five years."

It has been observed that many of the large infrastructures are migrating from Large Single unit to Multiple- unit constellation to better mitigate risks on reliability, performance, cost, deadline and technology (i.e. Starlink). The DSR architecture is composed of more than 100,000 fully replicable modules and components, ensuring speed and reliability in the scale-up process *(Figure 46).* This design allows an efficient industrialization process and an iterative deployment with benefit from any lessons learned of the first launches.

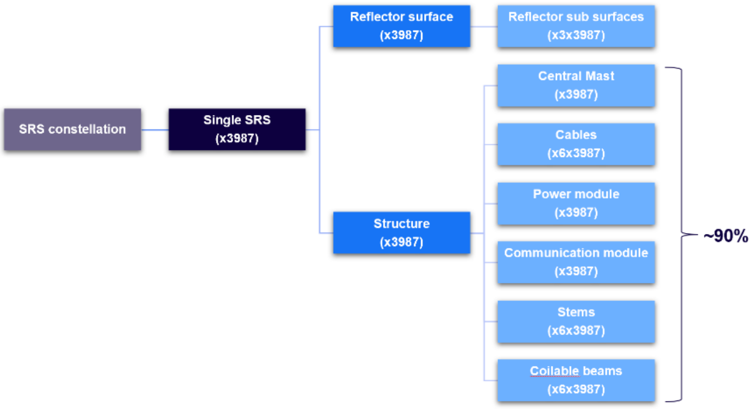


Figure 46 - DSR architecture

In terms of scalability, the launching capacity is the main bottleneck for deploying the DSR architecture as soon as possible (*Table 24*). Regarding the ground segment, as DSR is compliant with any solar farms, the infrastructure is fully scalable. Gaining the permitting of new locations could however be an issue and must be initiated as soon as possible (7-9 years of instructions).

Domain	Key scalability capability	Scalability assessment (Low – High)	Remarks
Critical material & supply chain[1]	Material & supply chain for DSR station		• KEEP could be an issue for very thin dimension (4 micron) but the material is available • Other material can be used in case of scarcity
Industrial manufacturing throughput	DSR station production plant		• Dedicated plants will be needed to industrialize the process and reduce the cost • Plants will also be built by several modules
Launch & Deployment	DSR station launching		• The maximum launch cadence and the fairing size limit the possibility to deploy quickly. • PROTEIN capability are key for deployment • Additional launching capability with Starship
	DSR assembly in space		• Folded DSR can be launched in case of problem if any delay in in-orbit infra deployment • 2 platforms and 6 robots is easily scalable

Table 24 - Space segment scalability assessment

12. RISK ANALYSIS

SECTION KEY MESSAGES

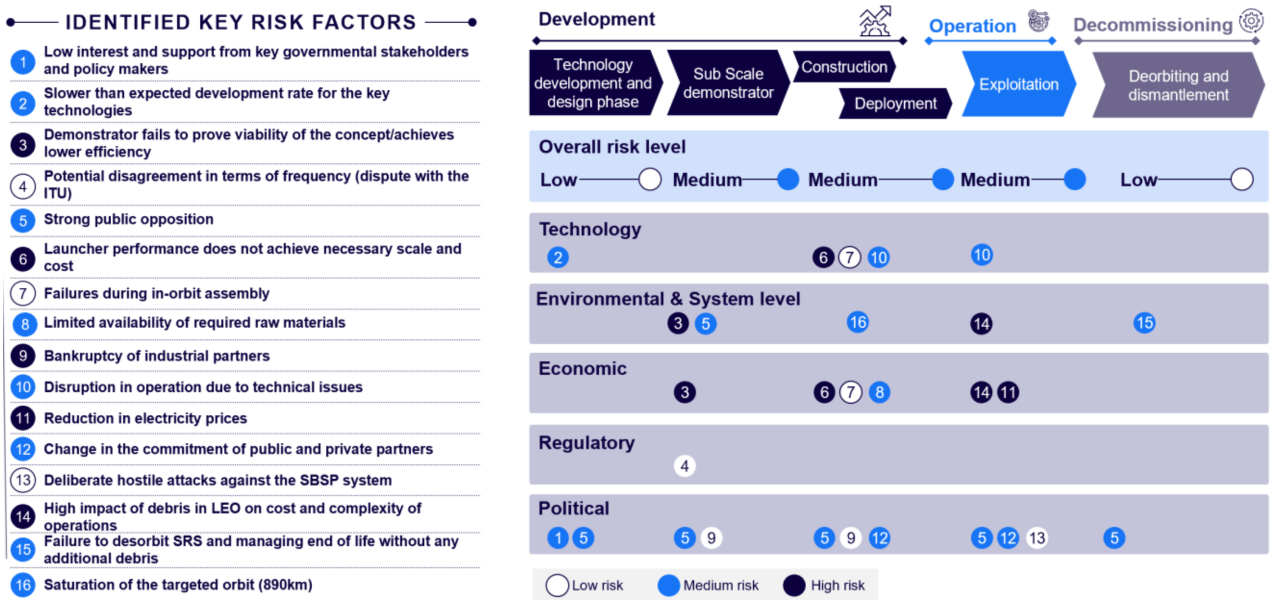
- Most of the potential risks are mitigated with DSR concept.
- Main risks in the technology development and design phase include limited support from policymakers/stakeholders and a slow rate of enabling technology development.
- The main risk in the sub scale demonstrator design phase is a slow rate of enabling technology development or not proving the estimated efficiency.
- Main risks in the construction and deployment phase include issues with reusable launch systems/in-orbit assembly as well as limited availability of raw materials.
- Main risks in operations, deorbiting and dismantlement phase include price decrease and potential accumulation of collision-generating debris.
- A critical risk to mitigate is the collision risk management, described in a separate part.

A first FDIR study for space segment has identified 6 critical risks (*Table 25*) and their associated detection methods and consequences on the space architecture. The three major critical events with the highest likelihood to occur are:

Risk	Risk nature	Detection	Effect	Measures
Collision with micro space debris	Critical events	Alert from Space Situational Awareness organization	Reflector damage. From minor to critical. Generation of debris.	• *Size the critical elements of the platform accordingly, protect with a shield to avoid any new deris* • *Use next generation of space debris tracking* • *Perform orbital and/attitude maneuvers for collision avoidance* • *Impact manageable with usual actions used for LEO constellation* • *Control modules' size is significantly lower than the mirror size* • *Replace reflector by a spare reflector*
Collision with micro space debris (not indexed in catalog)	Critical events	Structural sensors (strain gauges, shock detectors), camera inspection	Reflectors alteration. Depending on the impact energy and location	• *Size the critical elements of the platform accordingly and select a resistant material* • *Let it go and change mirrors after several years* • *Stick patches with robots*
Collision with micrometeroids	Critical events	Structural sensors (strain gauges, shock detectors), camera inspection	Reflectors alteration. Depending on the impact energy and location	• *Size the critical elements of the platform accordingly and select a resistant material* • *Let it go and change mirrors after several years* • *Stick patches with robots*
Collision with other reflectors of the fleet	Critical events	Flight dynamics collision alert	Reflectors destruction	• *Design of the constellation with enough distance between reflectors to let time to react (10x of the diameter of the platform)* • *Accurate and permanent relative orbital control*
Loss of attitude control	Fault	Sensors and TM and ground monitoring	Beam hazardous orientation on Earth	• *Beam interruption system. Attitude recovery program. Space servicer intervention.* • *Limit the max power beam of a unit reflector*
Reflector hacking	Critical events	From abnormal behavior to a sudden total loss of control	From abnormal behavior to a sudden total loss of control	• *Satellite crypto protection and monitoring software Limit the max power beam of a unit reflector*
Satellite too bright	Fault	From modeling at conception. From ground visual observations after launch. In Satellites in orbit getting lit up	Environnemental disturbance Other satellite disrturbance	• *Design of the platform (geometry, material) limiting unexpected reflecting surfaces.* • *Attitude control to avoid to direct the beam towards Earth when not on a PV farm* • *Natural sun irradiance is similar to us from DSR*
Major solar storm	Critical events	Avionics and communications anomaly	Avionics damage. Up to reflector control loss.	• *Size the avionics to survive major solar storms.* • *Space servicer spacecraft assistance for attitude and orbit recovery and repare.*

Table 25 - Identification of technical critical events

A risk analysis has also been performed on the entire life cycle of the DSR, from the development of the technology to its decommissioning, and has enabled to identify 16 risks which have been classified based on macroeconomic factors (technology, environmental & system level, economic, regulatory, political).



Main risks in the technology development and design phase include limited support from policymakers/stakeholders and a slow rate of enabling technology development (*Table 26*). For the sub-scale demonstrator design phase, the major risk is a slow rate of enabling technology development or not proving the estimated efficiency (*Table 27*). Regarding the construction and deployment phase, potential risk s could be the issues with reusable launch systems/in-orbit assembly as well as limited availability of raw materials (*Table 28*). Finally, main risks in operations, deorbiting and dismantlement phase include price decrease and potential accumulation of collision-generating debris *(Table 29).*

ID	Risk type	Risk category	Description	Root causes	Probability	Impact		DSR mitigation actions and resulting proba x impact	
01	Technology developm. & design phase	Political	**Low interest and support** from key governmental stakeholders and policy makers	• Key decision makers and stakeholder might be hard to convince about the feasibility of the concept, compared to other investments		• **Difficulty to gather financial and political support** for R&D and demonstrator project		• Demonstrate the DSR has low risk but high potential value with a progressive funding plan	
02	Technology developm. & design phase	Technology	**Slower** than expected **development rate** for the key technologies	• Unexpected barriers during development • Limited financial support for R&D		• **Delayed pilot**/demonstrator project **and deployment** compared to original schedule		• Almost all technologies are mature (except debris mitigation) • Progressive demonstrator with Go/NoGo milestones	
05	All phases	Political	Strong **public opposition**	• Fear of and/or uncertainty about the health effects • Visual pollution and fear of environmental damage		• The **protest of global and local communities** can delay the construction of the project (esp. the ground elements)		• Insist on natural illumination and limited irradiance • Locate ground power stations in inhabited areas	

Table 26 - Major risks for technology development

ID	Risk type	Risk category	Description	Root causes	Probability	Impact	DSR mitigation actions and resulting proba x impact
03	Sub Scale demonst-rator	Technology/ Economic	**Demonstrator fails to prove viability** of the concept/**achieves lower efficiency**	• Unforeseen technology barriers • Impossible to mitigate debris collision risks • Increased complexity of system due to scale-up		• System **cannot achieve the estimated efficiency** or can only achieve with increased mass leading to **higher cost**	• Progressive demonstrator with Go/NoGo milestones • **Include in the SSD plan back-up technologies**
04	Sub Scale demonst-rator	Regulatory	**Potential disagreement regarding** the **frequency** of the microwave (dispute with the ITU[1])	• Uncertainty around the long- term health implications and safety		• **Failure to secure the required frequency** can lower potential efficiency and power output	• No frequency request • Environmental studies to prove that DSR has no danger
09	Sub Scale demonst-rator Construction & deployment	Political	**Bankruptcy of industrial partners**	• Financial crises or debt issue linked with investments needed by DSR		• Delay in the deployment plan to find another partner • Program stopped	• Large companies involved • Progressive milestones and deployment

Table 27 - Major risks for SSD

ID	Risk type	Risk category	Description	Root causes	Probability	Impact	DSR mitigation actions and resulting proba x impact
06	Construction & deployment	Technology/ Economic/ Environmental	**Launcher performance does not achieve necessary scale** and cost by the time of construction & deployment	• Slower than expected development of fully reusable launch system		• **Increased cost of deployment** can lead to less competitive LCOE as more launches are needed to deploy the satellite	• Starship could use as a launcher • Modular architecture that support delays
07	Construction & deployment	Technology/ Economic	**Failures during in-orbit assembly**	• Disruption in communication with assembly units/robots • Collision with space debris		• **Increase construction time** and overall deployment cost	• Direct to Orbit deployment is sub-optimal but possible
08	Construction & deployment	Economic	**Limited availability of** required **raw materials**	• Disruption in global supply chains		• **Increased construction cost** and delayed deployment • **Increased dependency**	• Modular architecture with iterative designs than can support several materials (ex Kapton vs Keep)
10	Construction & deployment	Technology	**Disruption in operation due to technical issues**	• Space infrastructure no more controllable		• **Loss of control** • **No energy provided**	• SRS will burn in atmosphere withour danger • No safety risks
12	Construction & deployment Exploitation	Political	**Change in the commitment of public and private partners**	• No more deployment in space • No more fund		• **Lack of SRS to produce the outputs requested**	• Modular architecture, with impact possible with quite few mirrors

Table 28 - Major risks for construction & deployment

ID	Risk type	Risk category	Description	Root causes	Probability	Impact	DSR mitigation actions and resulting proba x impact
11	Exploitation	Economic	**Reduction in electricity prices**	• Maturity and scale effect of other renewables energies • Price war and political pressure		• **None economic viability of the program**	• Deployment on several ground infrastructure • **Develop back up technologies to control the beam**
13	Exploitation	Political	**Deliberate hostile attacks** against the SBSP system	• Political and/or armed conflicts between nations		• **Partial and full destruction** of the system	• Constellation wit multiple reflectors, nis security risks and complex to destroy
14	Exploitation	Economic	**High impact of debris in LEO on cost and complexity of operations**	• Millions of very small debris could jeopardize the efficiency of the reflectors		• **Complexity to replace mirrors** • **Additional OPEX that could impact the viability of the program**	• Multiple strategies to limit the impact f debris • **Assess several technologies to mitigate debris**
15	Deorbiting & dismantle	Environmental	**Failure to move to recycling and controlled return to earth**	• Failure of recycling systems		• **Accumulation of large amount of space debris** that can jeopardize future launches	• Multiple strategies to dismantle • Assess several technologies to mitigate debris

Table 29 - Major risks for operations, deorbiting and dismantlement

13. TECHNOLOGY DEVELOPMENT REQUIREMENTS

SECTION KEY MESSAGES

- Most of the required technologies are available and mature to deploy the DSR architecture.
- However, development efforts are needed in space to bring SPL to maturity, and in-space manufacturing for multiple mirrors, and on ground to bring solar fuel cells to maturity.
- To avoid debris collision risk, DSR could be deployed in a LEO orbit (2,400km or +) but would increase the number of mirrors except if SRS can concentrate the light.
- CL could be a complementary option to DSR to provide focused energy on a fewer ground power stations, especially in Europe.
- There are a lot of synergies between these two dual tracks to avoid any divergence.
- Strong efforts needed to bring solar fuel cells to maturity.
- European consortium counts an increasing number of industrial players launch solar fuel production program.
- The pilot projects will help to mature the needed technologies on the ground, even if the PV and electrolysis are mature technologies and could be used immediately.

Today, the overall DSR system is at a low maturity level (TRL = 1), even if most of the tehcnologies used are more mature, either on the space or ground segment.

13.1 SPACE SEGMENT

Considering the space segment, strong development efforts are required to bring SPL to maturity, and in-space manufacturing for multiple mirrors. The space assembly, maintenance and servicing building block is currently in 2023 at a medium TRL of 6. It is expected to reach a TRL of 8 to 9 by 2040. Some examples of enabling technologies are in-space Manufacturing, additive manufacturing, advanced autonomous robotic arms, self-deploying large structure (including membrane) or collapsible beams (by improving existing ones). Technologies to manage end-of-life (dismantling or recycling) are however less developed: the current TRL is at 1, and is expected to reach 3-4 by 2030 and 7-8 by 2040. Since end-of-life facilities are required only for the SRS decommissioning, after 30 years of operations, it gives some time to mature the technology.

The concept of the Coherent Light in GEO has been explored and adjusted since the last ASR review to avoid any security and weaponization risks. The initial Solar Coherent Light concept planned to deploy each SPL in GEO and illuminating a 230m diameter spot size with a 1,000 W/m^2 beam. If the system is hacked, it could be possible to focus all the beams on the same small spot, creating a dangerous power on the target zone. This critical issue pushes to reject the idea, despite its interesting potential. For AKR, the concept has been reviewed and is now called Coherent Light. The concept is similar to DSR: each CL in GEO illuminates a 3km diameter spot size with a ~10W/m^2 beam. The sum of all their illuminations represents 1,000W/m2, but there is no risks or danger because the power sent by a single CL will be diffused to limit to only 10W/m^2 on the ground. It could be a back-up adaptation in case of red flag for DSR LEO due to collision risks.

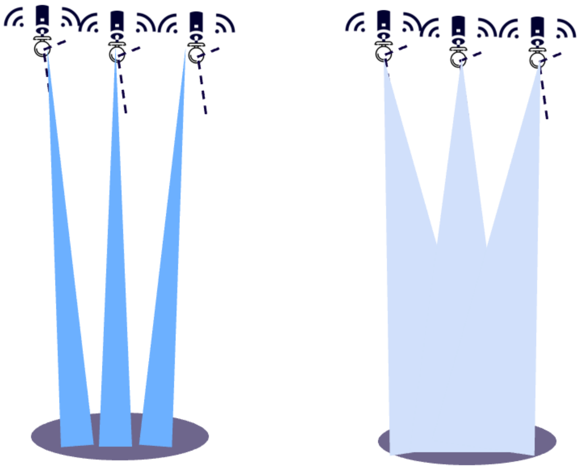


Figure 47 - Initial SPL concept (left) and new CL concept (right)

Due to the critical risk about collision management, we propose a dual track for the sub scale demonstrator. CL could be a complementary option to DSR to provide focused energy on a fewer GPS, especially in Europe. At small scale, CL is more advantageous because for the same energy delivered to one GPS, CL (with 10% efficiency) only launches 12,000 tons while DSR launches 3 to 4x more (45,00 tons). However, on the larger scale, to illuminate more stations, CL requires to deploy other space infrastructure which becomes very massive (*Figure 48)*.

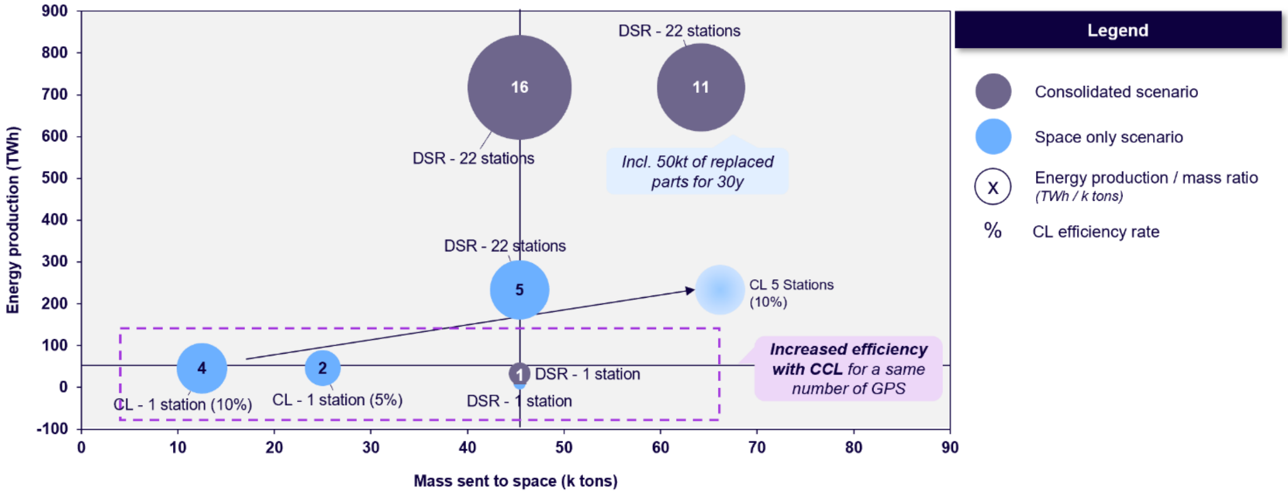


Figure 48 - Performance of DSR and CL

Although there are a lot of synergies between these two technologies, major issues for each have to be fixed during the SSD phase and have been summarized below (*Table 30)*.

Key technological issue	DSR concept in LEO	CL concept (coherent light) in GEO
Secure the feasibility to deploy large structure with mitigated risks of collision	**Critical** *(See § in this document)*	**Low** Low collision risk in GEO
Test the CMGs large capacity	**Critical** to ensure the agility of DSR	**Moderated** as the large structures will be quite stable and with low speed
Test the performance of solar pumped light	*Not concerned*	**Critical** to ensure the feasibility of the concept
Test the assembly of large mirrors	**High** To deploy in space. Can be assembly on earth if needed	
Test the reflecting shape resistance to reach 95%	**High** Impact the number of mirrors to produce 1000W/m2	
Test the unfolding process	**Critical**	
Test the solar sailing process	**High** To avoid using fuel to get to the final orbit	

Table 30 - Main issues to fix for the SSD phase

13.2 GROUND SEGMENT

Considering the ground segment, PV is a fully mature technology and PV+ELY has also a high maturity level. However, strong efforts are needed to bring SFC and floating PV to maturity. Currently, solar panel which convert directly sun into hydrogen (like SFC) have a TRL of 4, which is forecasted to reach 7-8 by 2030. Floating PV technology has as of now a TRL of 2, which is projected to increase to 3-4 by 2030 to finally reach 7-8 by 2040.

In Europe, an increasing number of industrial players launch solar fuel production program like Sun to X *(Figure 49*)

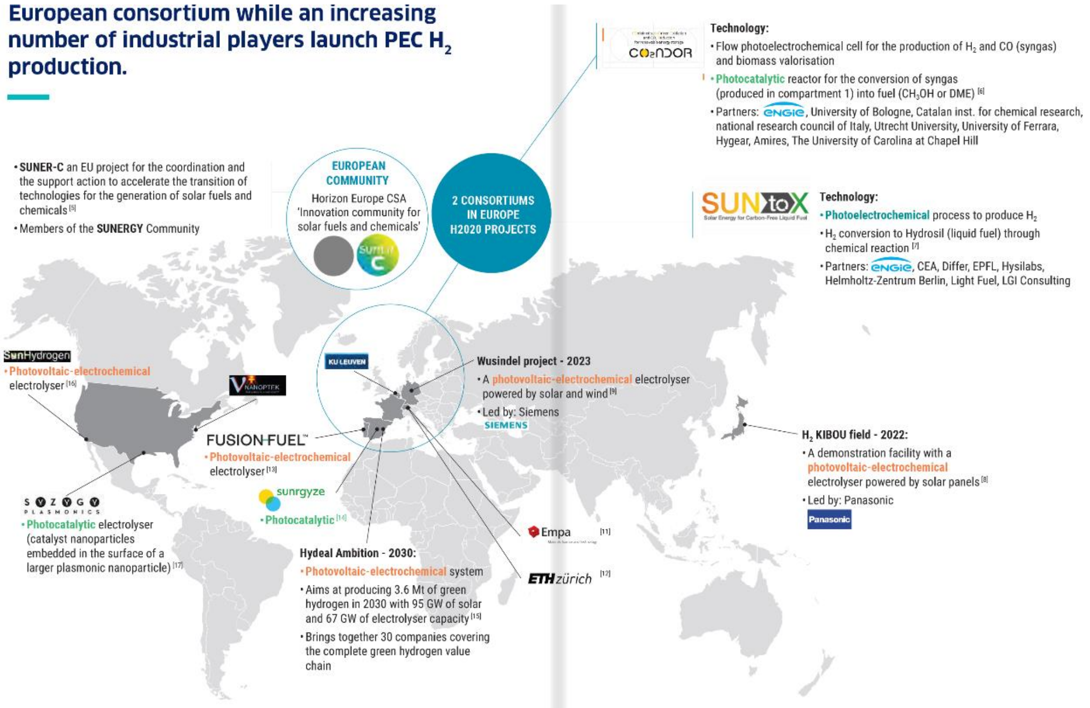


Figure 49 - Mapping of solar fuel program in Europe

14. ROADMAP DEFINITION

SECTION KEY MESSAGES

- The global roadmap until full scale deployment is based on six main workstreams that includes the design of the sub scale demonstrator starting in 2024 until the full-scale deployment in 2043.

The global roadmap until full scale deployment is based on six main workstreams:

- **Demonstrator** – Develop a sub-scale demonstrator to **validate the key components** of the space and ground segments *(2024-2029)*
- **Technology maturation program –** Mature the key technologies mainly on space *(2024-2028)*
- **Facilities building –** Build the main facilities to industrialize the production of the SRS *(2026-2036)*
- **Full scale DSR deployment** – Produce, launch, deploy and operate the SRS in space *(2031-2081)*
- **Stakeholders' alignment and infrastructure building** – Involve the ground operators and other stakeholders to convince on the DSR value. Build the additional ground power stations to ensure the right output sizing *(2028-2081)*
- **PROTEIN interface** – Coordinate with the PROTEIN project to ensure the feasibility to load 3 SRS in a single launcher for LEO 98° at the best costs and minimum CO2 footprint *(2024-2081)*

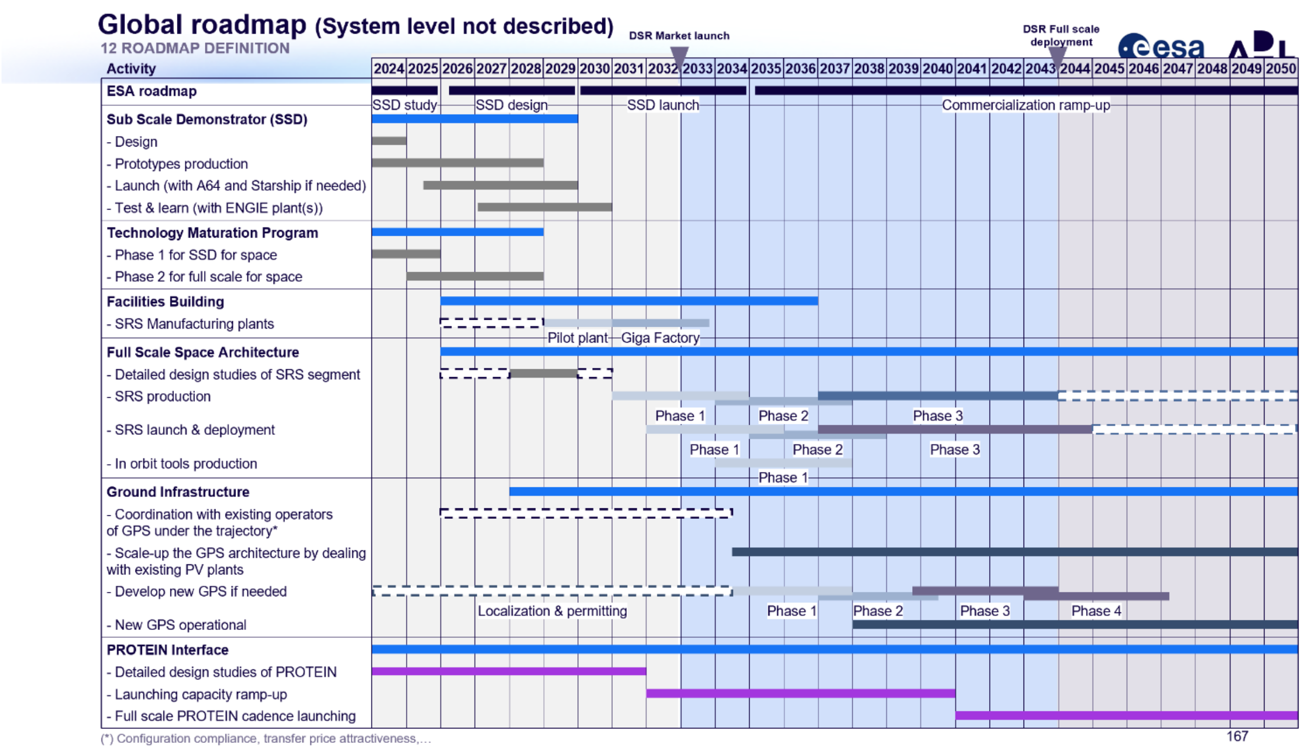


Figure 50 - Global roadmap (System level not described)

15. RECOMMENDATIONS FOR A SUB-SCALE-BASED DEMONSTRATOR

SECTION KEY MESSAGES

- Our approach is to keep the momentum of the project with key milestones until MVP end of 2030 at the latest.
- Proposed Design Phase Roadmap for the Sub Scale Demonstrator target a first reflector in space end of 2025.
- The priority is to de-risk the collision risk management policy of the SRS architecture, with eventually considering alternative options like SRS in GEO or using Concentrated Coherent Light in GEO

The demonstrator is the first step to further study key points of the infrastructure to derisk the main issues linked with DSR performance. During the sub-scale demonstrator phase, a few considerations for each ConOps must be assessed:

- **Assembly** – SRS deployment autonomy
- **Attitude control & Maintenance** – Rotation rates, Control strategy, Impacts of vibrations
- **Collision risk management** – Membrane deformation, Structure reinforcement
- **End-of life** – End of life policy

These considerations are summarized in the *Table 31* with potential solutions to be further assessed and actions planned during the SSD.

ConOps	Questioning	Solutions under consideration to be further analyzed	Actions planned during the demonstrator phase
Assembly	• Can SRS be deployed autonomously ?	• Use the NASA design	• Full simulation + test of the first SRS launched
Attitude control & Maintenance	• Can the structure withstand the proposed rotation rates?	• Structure composed of two control systems: CMGs and secondary actuators with a mass	• Detailed analysis • Full simulation
Attitude control & Maintenance	• What is the control strategy for a flexible structure?	• Implementation of a control system for flexible structure: SSD will be representative of the structure's flexibility	• Detailed analysis • Full simulation • Test on the first SRS launched
Attitude control & Maintenance	• How do vibrations caused by CMG will impact the structure dynamics?	• Flywheel is projected to be perfectly balanced to avoid any vibrations	• Detailed analysis • Test in labo
Attitude control & Maintenance	• Where will be positioned the counterweight on the structure? • How will its movements affect the spacecraft ?	• The moving mass could in fact move in 3D, on most of the locations of the structure (rim, mast and spokes) • The motion of the counterweight is slow and essentially translations along the spokes and mast and its objective is to lighten the torques that CMG has to manage	• Detailed analysis • Full simulation • Test in labo • Test on the first SRS launched
Collision risk management	• How will impacts deform the membrane?	• PEEK material has been selected to avoid any extensive thrown of the membrane. The membrane is kept flat by peripherical tension	• Full simulation • Test in labo • Test on the first SRS launched
Collision risk management	• How can the structure be reinforced to limit the debris creation?	• Several options are considered to improve the membrane resistance: adding a layer of graphene absorbing debris, thinner and more rigid beams to reduce the surface exposed	• Detailed analysis • Full simulation • Test on the first SRS launched
End of life	• What is the best end-of life policy for each component of the SRS?	• Return to Earth by solar sail or with space tug • Return on parking orbit and recycling *(on longer-term)* • Selection of material that could be recycled	• Detailed analysis • Full simulation

Table 31 - Main considerations for the DSR system to be assessed during the SSD phase

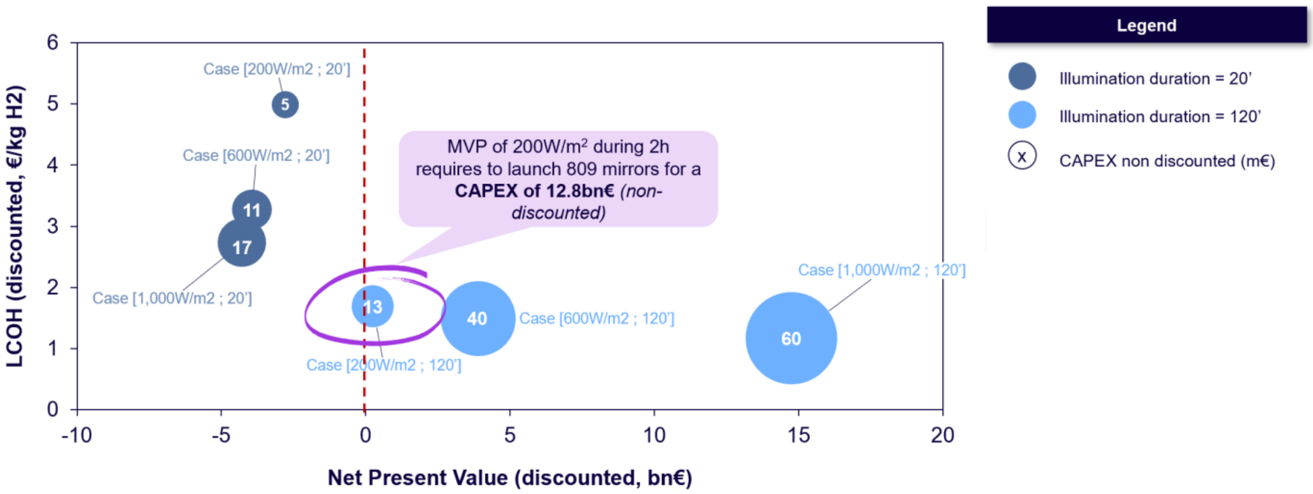
Four main milestones have been identified and analyzed to demonstrate the feasibility and viability of the DSR concept, which differ in terms of power sent and duration of illumination.

1. **Sub-scale demonstrator DSR (low power)**
   Its main objective is to demonstrate the flight capacity of the DSR by providing a minimum power to ground (10W/m^2) during only a few minutes (10’). It would require ca. 800m€ to produce 5 SRS and 100m€ for the launches, resulting in a NPV of -900bn€

2. **Sub-scale demonstrator DSR (medium power)**
   Similarly, to the first milestone, its main objective is to demonstrate the flight capacity of the DSR but with enough power to activate the PV cells on ground by sending 200 W/m^2 during 20’. It would require ca. 2.5 bn€ to produce 165 SRS and 2.8 bn€ for the launches, resulting in a NPV of -4.3bn€

3. **Minimum Viable Product DSR**
   This step will aim at demonstrating the value of DSR to ground operators by providing enough energy to activate the PV cells (200 W/m^2) during 2 hours at dusk or dawn with a minimum-cost MVP. It would require ca. 4.6 bn€ to produce 809 SRS and 8.2 bn€ for the launches, resulting in a NPV of 250m€. Initiating a MVP with DSR requires high CAPEX investment but DSR gets more advantageous on a larger scale, when producing 1,000 W/m^2 for example (Figure 51).

4. **Sub-scale demonstrator CL**
   The objective of a CL demonstrator is to deploy minimum infrastructure in GEO orbit to be profitable. It would require ca. 50 m€ to produce 5 CL and 100 m€ for the launches resulting in a NPV of zero.



Note: Deployment from 2032 using Starship & PROTEIN considering a lifetime of 30 years; No scale up in power and duration in the deployment considered in the simulation, it is assumed it will directly reach the target power and illumination; maintenance cost for mirror replacement excluded from calculation

Figure 51 - Profitability analysis based on power and duration of illumination

Main steps and a roadmap for the sub-scale demonstrator phase has been defined and targets the deployment of the first SRS in space by the end of 2025 (*Figure 52* and *Figure 53*). Before this milestone, further studies need to be conducted especially an assessment of the DSR environmental impact on ground and in space, and on the collision risk management in a LEO orbit. Further details on each step are provided in TN5.

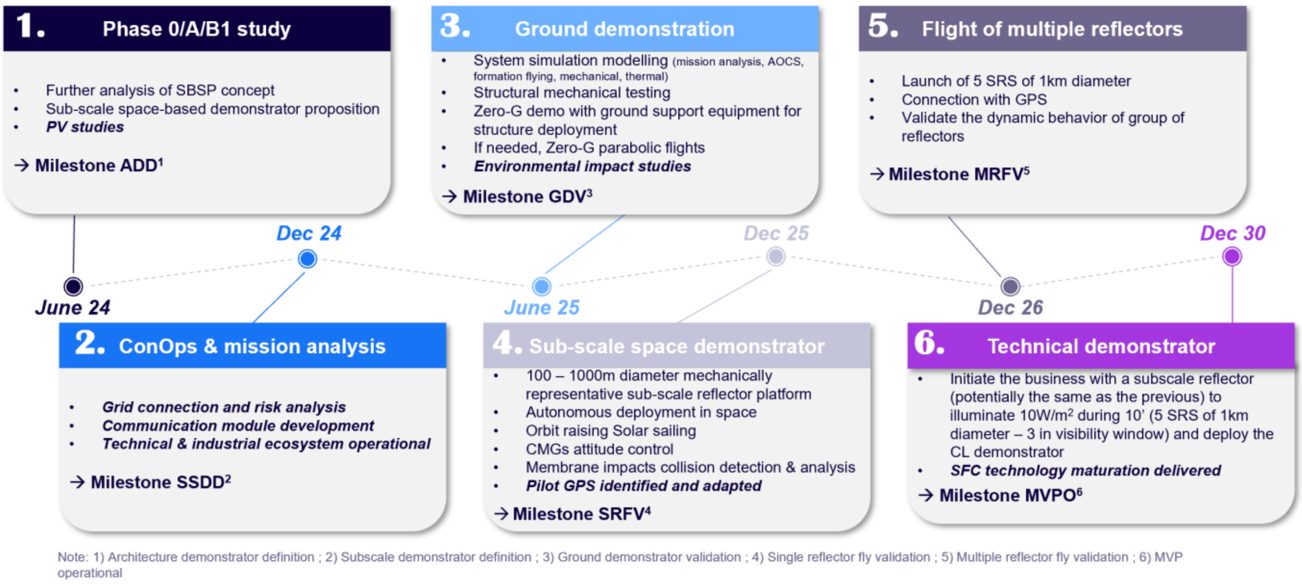


Figure 52 - Main steps for the SSD phase

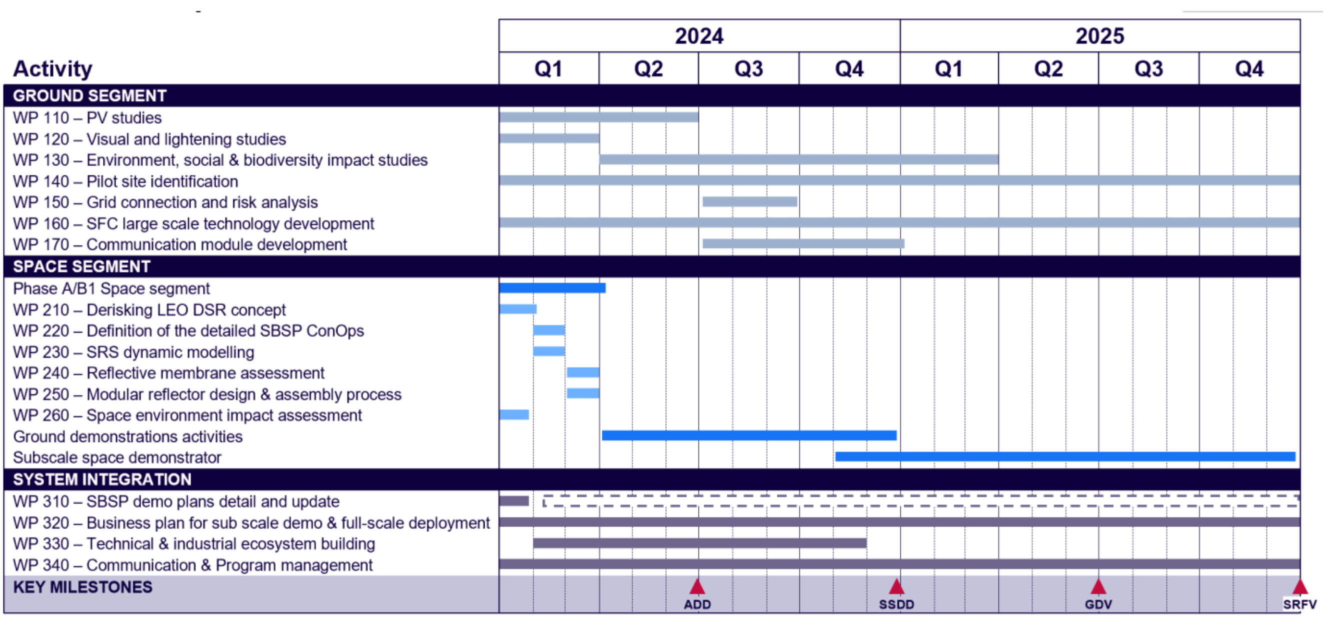


Figure 53 - Proposed Design Phase Roadmap for a SSD

CONCLUSION

Since the ASR review, some adaptations have been made on a few parameters such as the number of SRS to be deployed, the SRS individual mass or the number of required GPS. Yet, even with these adaptations, we can confirm the global competitiveness of the DSR concept (Figure 54).

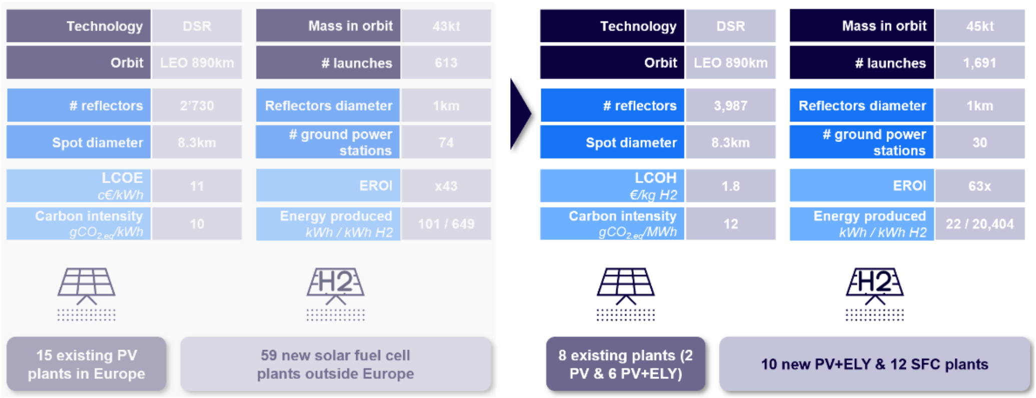


Figure 54 - Parameters and output from ASR (left) and AKR (right)

Furthermore, the DSR concept fully fits with ESA functional, mission, operational requirements. Regarding the physical requirements, and more especially the energy production, DSR concept supposes to invest in new GPS (in our case 22 new) to meet the targeted energy production of 750 TWh per year or 10% of the European hydrogen consumption forecast in 2050.

There is though a remaining concern regarding the zero-space debris requirement: the debris collision risk management is the main concern that could limit the competitiveness and the feasibility of the global DSR concept. There is no perfect solution, but DSR offers several key success factors for providing energy from space *(Figure 55)*. However, the pre-study raised a critical issue concerning the huge number of small debris that could impact each mirror. Fixing this issue is a major workstream of the SSD and should be completed by a back-up solution as it appears to be a red-flag. We consider that Coherent Light is a back-up solution that should be assessed more deeply, as GEO orbit is not so strongly concerned by debris collision, and many points in the DSR pre-study could be leveraged.

Strengths	Weaknesses
• Competitive in terms of LCOx, energy and CO2 footprint • Space backbone can be amortized with the value provided to third parties • Leverage existing infrastructure and stakeholders' ecosystems • Replicable modular architecture compatible with fast and secured ramp-up	• Very high volume of debris collision on each cm2 of each mirror in the selected LEO orbit • Large amount of investment non compatible with private funding • Fitting locations of ground power stations and trajectory could be an issue
Opportunities	**Threats**
• Could benefit from disruptive technologies on PV and hydrogen production • Large support from government on hydrogen all over the world (Africa, Middle-East, Europe...)	• Price decrease could impact the transfer price to ground power stations and impact the viability of the architecture • Public acceptance could be issue, although the natural illumination only on dawn and dusk

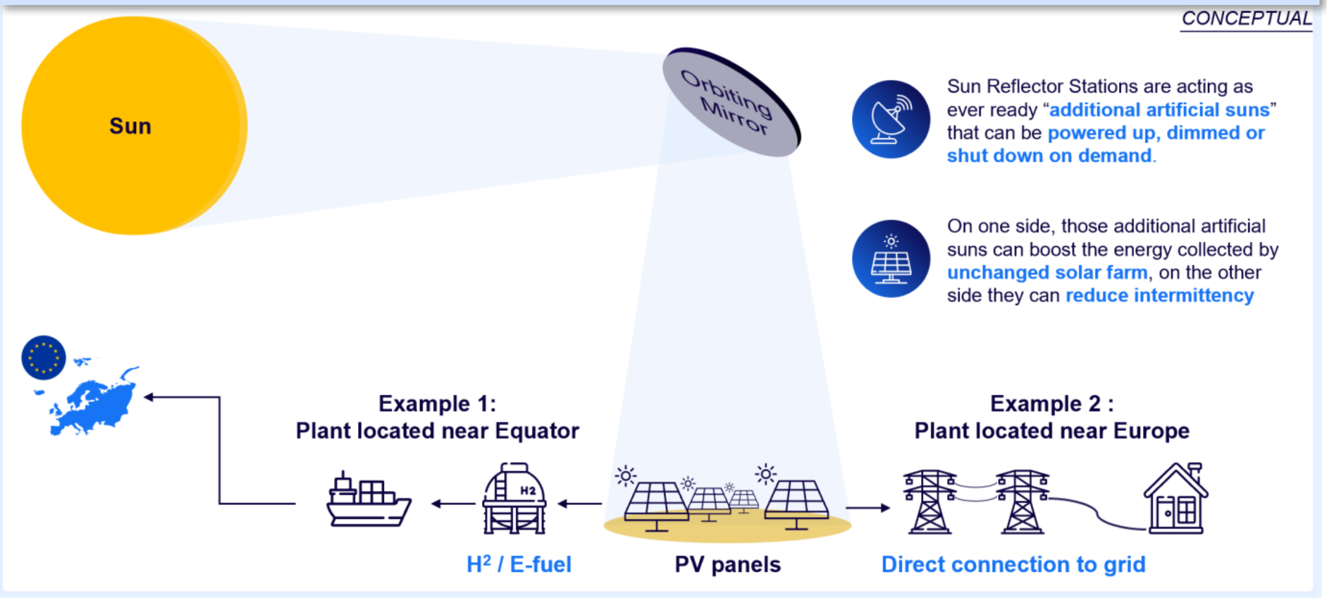
Figure 55 - SWOT analysis of the DSR concept

APPENDIX

REMINDER OF THE PRE-STUDY APPROACH

SECTION KEY MESSAGES

- The DSR concept is based on increasing sunlight on photovoltaic panels by redirecting the solar light via reflection panel on satellites.
- The DSR concept is not new, and several studies has been developed for lighting or energy supplying, limited until now by technology hurdles or cost competitiveness.
- Our DSR architecture has several potential use cases that will contribute to amortize the total cost of ownership.



1929	1967	1970	1979	1982	1990'	2020'+
Hermann Oberth	A.G. Buckingham	Krafft A. Ehricke	Kenneth W. Billman Krafft .A. Ehricke	NASA	Znamya	John. C. Mankins SolSpace, Mirasolar
Concept of orbiting mirrors to reflect sunlight to earth	**DSR for illumination purposes**	**Use cases for "space light"**	**SOLARES & SOLETTA constellation design**	**System design of DSR for illumination**	**First deployment**	**Solar power momentum**
• Mathematical demonstration of the concept. However, **technology was not advanced enough to implement it.**	• **Illumination use cases analysis,** including **military applications** (Vietnam war). • **Existence of technology** to fabricate and launch large solar reflectors, **projects** cancelled due to the anticipated early end of the war.	• Identification of "space light" use cases: **illumination, improving plant growth, generating electricity,** and **controlling climate.**	• **SOLARES program:** 80 000 orbiting solar reflectors to produce 220 GW of electrical power. • **SOLETTA constellation** at 4200 km, delivering up to 180 GW of power with a 42 km diameter spot on Earth.	• **Synthesis of physical equations** for illumination from space.	• Russian space-mirror experiment **illuminates 5km diameter wide spot** from Southern France to western Russia	• Several updated studies about **orbiting solar reflectors for power plants** have being presented (73rd International Astronautical Congress, Paris, in September 2022)

Solar energy collected in…
- Uninhabited area in desert near the equator (outside Europe)
- Isolated country-side area in Europe
- Off-shore platform in a sea near the Europe coasts

… and transformed in…
- Hydrogen or other[1]
- Heat or warming
- Electricity directly for a grid
- Light

.. to be used by…
- Hydrogen provider
- Local industrial[2] or farmer near the GPS
- e-Fuel provider (or equivalent)
- Electricity provider
- Electric network operator

…located…
- In Europe
- Outside Europe

…for a final use in…
- Industrial or chemical process
- Green heavy mobility (road, train, maritime, aviation)
- EV and other hourly electric use cases
- Buildings sector
- Agriculture

…allowing to…
- **Get green H2 at scale instead of fossil energy with no extension of CAPEX**
- **Get clean energy without any storage needs**
- Accelerate the photosynthesis

The objective of "DSR Space Co" is therefore to:
- Define a "transfer price" attractive for ground operators and sufficient to be viable and profitable
- Acquire enough "customers" on earth to load the space infrastructure and cover the total cost of ownership

Note: (1) E-ammoniac, e-methanol…, (2) Institutional users such as chemical plants, military bases, isolated towns, large mining and manufacturing operations, electric rail transportation systems

KEY PARAMETERS ASSUMPTIONS FOR SPACE SEGMENT

IMPACT[1]

RELIABILITY[2]	Low	Medium	High
Low			• **Reflection coefficient** • **Individual 1km diameter reflector mass** • **Structure weight** • **Starship launching costs** • **Satellite construction cost** • **Space maintenance costs**
Medium	• A64 launching costs	• Satellite construction emissions	• Mirror diameter • Starship launching capabilities • PROTEIN launching costs • PROTEIN launching capabilities & cadence • Launch emissions (incl. all preparations) • Launch emissions (incl. only fuel burned)
High	• SRS efficiency on deployment year • Satellite construction cost spread • Cost for running space operations	• Minimum elevation • # flights above equatorial stations • SRS lifetime • A64 launching capabilities	• Average irradiation without SRS • Orbit altitude • Argon & Krypton cost

Note: 1) Assessment of the impact of the selected parameters on the output parameters LCOE, EROI and CO2 emitted ; 2) Assessment of the parameter value reliability and coherence with other sources

Key parameter | **Individual 1km diameter reflector mass**

▶ Used for **overall space segment mass** to be launched and **reflector inertia**

Assessment

Impact	High
Reliability	Low

Values & Sources

9.3 tons	NASA
11.4 tons	TAS

Low-end / High-end limit

9 tons	12 tons (+33%)

RATIONAL

- The reflector architecture has been inspired from **NASA-CR-3438 1981006602 study**
- The overall mass of the structure is really dependent on the technology and architecture selected
- The mass assumption for a 1 km reflector is higher compared to NASA because of:
  - **Bigger CMGs** due to **higher attitude control** needs required by a lower orbit
  - Complementary system (center of mass positioning)
- Consolidation would require further iterative sensitivity analyses of the "architecture-mass-inertia-AOCS" loop.

Key parameter	PROTEIN key parameters

▶ Used to compute **launching costs**, included in **space segment CAPEX**

Assessment	
Impact	Medium
Reliability	Medium

Values & Sources

See table below	PROTEIN Consortium

RATIONAL

- PROTEIN Consortium 1 estimates the total launch cost at **20 m€ in 2035** for a single launcher in Direct-to-Orbit, compatible with ESA target launch cost.
  - Our strategy to make solar sailing will extend the delay but will not impact the cost
- Estimations are considered for a 1) **two Stage To Orbit** (TSTO) launcher, 2) **full reuse** launcher and 3) **Return To Launch Station** (RTLS) strategy

		PROTEIN Consortium 1		PROTEIN Consortium 2		Selected values
	Unit	DtO[1]	L&SF[2]	DtO[1]	L&SF[2]	L&SF
Launching capacity	tons	49	51	43	64	**51**
Total launch cost	m€	20 in 2035		n/a	n/a	**20 in 2035**
Max number of launch per year	#/y	135 in 2035	134 in 2035	100 in 2040	74 in 2040	**134 in 2035**
Energy required	GWh/launch	28		89		**50**
CO2 emitted	ktCO2e/launch	54		41		**50**

Key parameter	Launch emissions (incl. all preparations)

▶ Used to compute the **carbon footprint of the launching phase**

Assessment	
Impact	High
Reliability	Medium

Values & Sources

73 ktCO2/launch	PROTEIN baseline
40 ktCO2/launch	PROTEIN sustainable
50 ktCO2/launch	PROTEIN average

Low-end / High-end limit

8%	13%

RATIONAL

- The life cycle emissions are given per launch for the scope 3 and derived from the propellant type and mass used in the respective vehicle design.
- The TSTO RTLS[1] configuration has a LCE of 73,238 t CO2e per launch, if a single vehicle is reused 32 times. Deploying the constellation planned would require 896 launches and result in total emissions of ~65 megatons of eCO2 ("Baseline" case)
- These emission could fall dramatically if the supply- & manufacturing chain is sustainable and decarbonized. If such a decarbonisation should be implemented, the complete LCE would fall to ~36 megatons of eCO2 for the deployment of the complete SBSP ("Sustainable" case).
- Materials used for the launcher construction are mostly stainless steel and CFRP[3].

	Propellant volume for a TSTO[2]				
	Density	First Stage Tank Volume	First Stage Propellant Mass	Second Stage Tank Volume	Second Stage Propellant Mass
LOX (Liquid Oxygen)	1,141 kg/m^3	~1,308 m^3	~1,491 tons	~339 m^3	~386 tons
CH4 (Liquid Methane)	421.1 kg/m^3	~1,012 m^3	~426 tons	-	-
H2 (Liquid Hydrogen)	70.9 kg/m^3	-	-	~902 m^3	~64 tons

Note: 1) Two Stage To Orbit with a Return To Launch Station ; 2) assuming the volume is completely filled with the respective propellant ; 3) Carbon Fiber Reinforced Polymers

Key parameter	Reflection coefficient

▶ Used to compute the **power delivered by DSR** in minimum spot

Assessment	
Impact	High
Reliability	Low

Values & Sources

82%	NASA[1]
92%	Solspace[2]
95%	TALDA analysis

Low-end / High-end limit

80%	98%

RATIONAL

- The reflection coefficient takes into consideration the energy loss of the illumination due to imperfect reflection and pointing errors
- NASA studies were conducted on the basis of a maximum rms gradient of 0.00082 rad, corresponding to an edge gradient of 0.001 rad for a spherically curved circular membrane. This corresponds to an **energy loss of 18%** of the illumination, which seems reasonable when compared to other losses due to imperfect reflection and pointing errors
- Solspace project assumed a **92% reflection coefficient** following earlier studies (Canady and Allen, 1982)
- **95%** has been selected considering that in the next decade **improvement on this topic especially new materials and management of large surface** will allow to reach this coefficient

Note: 1) "Conceptual Design Studies for Large Free-Flying Solar-Reflector Spacecraft", 1981, NASA ; 2) "A reference architecture for orbiting solar reflectors to enhance terrestrial solar power plant output", 2023

Key parameter	Satellite construction cost

▶ Used to compute the **space segment CAPEX**

Assessment	
Impact	High
Reliability	Low

Values & Sources

375 €/kg	Solspace[1]
325 €/kg	ADL analysis
300 €/kg	MPT studies[2]

Low-end / High-end limit

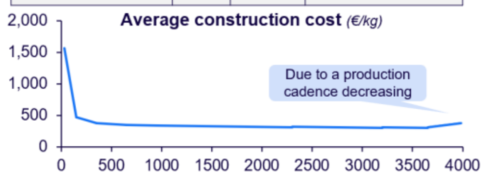
300 €/kg	1,000 €/kg

RATIONAL

- A **reflective membrane initially costs** 3.8m€ to be produced *(TAS, see opposite table).* Including structure costs, 8m€ is a reasonable estimation for initial SRS construction costs
- Being produced in large quantities, two factors have been considered in the computation of satellite production costs: 1) rate effects and 2) the learning curve effect *(figure opposite)*
  - **Cadence effect** decreases the fixed costs and variable costs per unit due to a high number of satellites produced (hypothesis of 40% at cadence 7/y and rank 7)
  - **Learning curve effect** leads to a fall in the cost of production per unit because of the increased experience over time (hypothesis based on Wright law with ration from 0.85 to 0.95 progressively) – *See next slide for benchmark*
- Considering these two effects, the global COGS for SRS production is **15.5 bn€** *(vs. 363 bn€ if no effects considered).* For **3,987 SRS** deployed, each weighting 11.4t, the average cost of production is **325 €/kg**

Reflective membrane construction cost

Membrane indicators	Unit	Value	Comment
Mass	g/m²	6	
Surface	m²	785,398	
Cost	k€/kg	0.8	Based on the cost of a 8µm and 25µm
TOTAL COST	m€	3.8	



Note : 1) "A reference architecture for orbiting solar reflectors to enhance terrestrial solar power plant output", 2023 ; 2) ESA studies for the microwave power transmission

	Constellation size (#)	Satellite mass (kg)	Total constellation mass (ton)	Constellation cost (bn$)	Cost per launched mass ($/kg)	Satellite lifetime (year)	Launch mass per satellite year (ton/year)
Starlinks	12,000	260	3,120	10.0	3.2	6	520.0
Kuiper	3,236	650	2,103	10.0	4.8	7	300.5
Lighspeed	198	750	149	3.6	24.2	11	13.5
OneWeb 2.0	300	750	45	4.0	17.8	7	32.1

- **Constellation size**
  - The constellation size is as announced for the cost
- **Constellation cost**
  - The constellation cost are the announced investment required for the constellation, including the ground segment. No further details between the split space / ground are provided in this analysis and therefore the cost per launched mass could be even lower
  - Starlinks has ambition of going to 42,000 satellites but the 10 bn$ announced is for the initial 12,000 satellites. Similarly, Lightspeed has had some iterations. The 3.6 bn $ is for the current 198 satellite constellation
- **Launch mass**
  - The launch mass per satellite year is the total constellation mass divided by the satellite lifetime and can be used as metric for the replenishment requirements for launching

	mass	Cost per kg	Rationale
Structure	7800	300	Carbn Epoxy is about ~50€/kg
KEEP	3100	1000	800€/lg s the commercial price given by the producer
Platform	384	3500	*See opposite*
TOTAL	**11 365**	**603 (6,862,000)**	**For the first SRS**

Sector	Learning rate	Learning type
Aircraft	19%	Man time learning
Shipbuilding	10 - 15%	
Semi-conductors	20%	
PV	20 - 35%	
Wind turbines	4 - 12%	Learning rate based on overall cost, including all types of improvement
Gas pipelines	4 - 24%	
Gas turbines	10%	
Coal power	8%	
Wind	17%	
Solar PV module	20%	
Nuclear plant	3%-10%	

Key parameter	WACC Space

▶ Used to compute the **discounted revenues, costs and energy generated by the DSR**

Assessment	
Impact	Medium
Reliability	Medium

Values & Sources	
10%	TALDA

Low-end / High-end limit	
8%	13%

RATIONAL

- The weighted average cost of capital is a financial metric used to determine the **discount rate** for evaluating the present value of future cash flows and making investment decisions.
- It depends on the company's **capital structure** (split between **debt and equity**). Its formula is the following:
- $WACC = \frac{Equity\ market\ value}{Debt\ market\ value} * Cost\ of\ equity + \frac{Debt\ market\ value}{Equiy\ market\ value} * Cost\ of\ debt * (1 - \text{Tax rate})$
- A **WACC Space of 10%** was considered for this project based on several factors :
  - It is **a large-scale project** with a **high level of risk,** yet this kind of project require **public investments** mitigating the risk
  - A feasibility study for a **small reactor module** conducted by the UK National Nuclear Laboratory estimates a **WACC of 9%**

Parameter	Unit	Value	Impact	Reliability	Source	Comments
Mirror diameter	m	1,000	High	Medium	TAS	
Orbit altitude	km	890	High	High	TAS	
Minimum elevation	deg	20	Medium	High	TAS	
Duration of illumination per day	h	2	High	Medium	TAS	
Number of flights above equatorial stations	#	2	Medium	High	TAS	• Stations with latitude between [-20° ; 20°]
Number of flights above non- equatorial stations	#	1.5	Medium	High	TAS	• Stations with latitude below -20° or above 20° • 1 flight for 2 hours + additional energy provided by flight outside peak hours to compensate sun illumination until 1000W/m2
SRS lifetime	years	30	Medium	High	TAS	
Launching capacity A64 DtO[1] / L&SF[2]	tons	14 / 21	Medium	High	ArianeGroup	Based on the use manual data

Note: 1) Direct to Orbit ; 2) LEO & Solar Foil

Parameter	Unit	Value	Impact	Reliability	Source	Comments
Launching capacity Starship DtO[1] / L&SF[2]	tons	70 /100	High	Medium	Starship	• Decreasing due to 98° inclination
Launching cost A64 (CAGR)	m€ (%)	100 (-2%)	Low	Medium	ArianeGroup	
Launching cost Starship (CAGR)	m€ (%)	100 (-8%)	High	Low	Starship	
Costs for running space operations	m€/y	7.5	Low	High	TAS	
Argon cost	€/kg	31	High	High	TAS	• Argon cost = Xenon cost / 800 • Xenon cost = 25,000 €/kg (x8 since military operation in Ukraine)
Launch emissions (incl. all preparations)	ktCO_2e	40	High	Medium	AGS	
Satellite construction emissions	ktCO_2e / ton	82	Medium	Medium	Berlin Space Technologies	

KEY PARAMTERS ASSUMPTIONS FOR GROUND SEGMENT

IMPACT[1]

RELIABILITY[2]	Low	Medium	High
Low	• Carbon emitted per panel complete lifecycle	• SFC lifetime • Stacks costs • Energy required to produce PV	• **SFC unit CAPEX** ⚠
Medium	• Energy required to produce ELY • Carbon required to produce ELY		• WACC • PV unit CAPEX • ELY unit CAPEX • SFC panel efficiency ratio • Carbon emitted per kWh electricity in Europe • Energy generated post PV & post SFC
High		• PV lifetime • Hydrogen energy content • Hydrogen energy conversion rate • Electrolysis vs solar PV capacity • PV, ELY and SFC O&M costs	• Coverage & Filling ratio • Incidence angle • PV to electricity efficiency ratio • Electrolyser ratio • Stacks replacement frequency • Installed capacity for Small & Large GS • Transfer prices

Note: 1) Assessment of the impact of the selected parameters on the output parameters LCOE, EROI and CO2 emitted ; 2) Assessment of the parameter value reliability and coherence with other sources

Key parameter	**Energy generated post PV**

▶ Used to compute **energy produced** by new GPS from **natural illumination** received

Assessment	
Impact	High
Reliability	Medium

Values & Sources	
1,000 kWh/m2	Engie
1,977 kWh/kWp	Engie[1]

Low-end / High-end limit	
1,000	2,500

RATIONAL

- According the World Meteorological Organization, climate stations around the world average **2,334 hours of sun a year**, equal to 6 hours and 24 minutes of sunshine a day
  - This produced about **2,334 kWh/m2/y** (with 1,000W/m2 of sun illumination)
  - The top 10 sunniest place in the world received 3830 kWh/m2/y
- Based on baseline site configuration, sun yield of **1,977 kWh/kWp** is the average of sun yields values from the nine pre-identified locations by Engie, excluding European and non-equatorial sites (see opposite)
- Reference parameter value : **1,977 kWh/kWp**
  - The assumption is made that new ground power stations will be built outside Europe because the weather conditions are better (higher sunshine and lower cloud coverage rate) and due to the intersite distance of DSR of 4000km avoiding illuminating many European on-grid sites
  - As we will have some flexibility to select the best location for our concept, it will be possible to find better conditions to produce H2

Simulation	Use-case	Coordinates	Location	Year-average clear-sky index[1]	Yield sun only [kWh/kWp.yr]
A	Mainland Europe	56.24N, 23.30E	Lithuania	60.8%	892
B	Floating Europe	38.64N, 27.9W	Azores	53.4%	1,042
C	Mainland non-Europe	14.46S, 75.7W	Peru	90.3%	2,147
D	Floating non-Europe	38.0S, 178E	N-Z	68.0%	1,425
E	Mainland non-Europe	48.86N, 94.0E	Mongolia	66.2%	1,321
F	Mainland non-Europe	30.39N, 115.76W	California	86.6%	1,889
G	Floating non-Europe	14.0S, 172.0W	Samoa	76.6%	1,787
H	Mainland non-Europe	17.38S, 12.2E	Namibia	97.2%	2,268
I	Mainland non-Europe	5.05S, 104.57E	Sumatra	68.8%	1,613
J	Floating non-Europe	35.19N, 140E	Japan	67.9%	1,401
K	Mainland non-Europe	26.84N, 57.56E	Iran	90.2%	1,897

Note: 1) Average sun yield of 3 equatorial location (Peru, Samoa, Sumatra) resulting from Engie analysis

Key parameter	Energy generated post SFC

▸ Used to compute **energy produced** by new GPS from **natural illumination** received

Assessment	
Impact	High
Reliability	Medium

Values & Sources

Value	Source
2,929 kWh/kWp	Engie

Low-end / High-end limit

1,480	3,700

RATIONAL

- Energy generated by natural illumination post PV is estimated at **1,977 kWh/kWp** for a PV to electricity efficiency ratio of **27%**
- SFC has a higher efficiency ratio compared to PV : it is estimated at **40%**
- Energy generated by natural illumination post SFC = 1,977 / PV efficiency ratio * SFC efficiency ratio = **2,929 kWh/kWp**

Note: 1) Average sun yield of 3 equatorial location (Peru, Samoa, Sumatra) resulting from Engie analysis

Key parameter	Installed capacity for large GS

▸ Used to compute **GPS costs (CAPEX & OPEX), energy and carbon emissions**

Assessment	
Impact	High
Reliability	High

Values & Sources

Value	Source
5 GWp	Global Energy Monitor
8.8 GWp	ADL[1]

Low-end / High-end limit

5	13,5

RATIONAL

- Electric power has been computed for a large GPS with a **surface of 50km²,** compatible with the spot size generated by DSR
- With this hypothesis, the 1,000 W/m² emitted by DSR to earth provides a power after atmospheric attenuation of **50,265 MW**
- Following attenuation ratio have been considered in the computation of the electric power (see opposite):
  - **Coverage attenuation**
  - **Filling rate**
  - **Incidence angle**
  - **Electricity conversion ratio**
- After attenuation, the electric power generated by a large GPS is **5,637 MW**
- Installed capacity is computed based on the **electric power generated after atmospheric attenuation but before coverage and incidence angle** to be able to accept the maximum of power in the ideal case

	Real production		Installed capa.	
	Ratio (%)	Power (GW)	Ratio (%)	Power (GW)
Power after atm. attenuation		**50.3**		**50.3**
Power after coverage attenuation	*90%*	45.2	100%	50.3
Power after filling rate attenuation	*65%*	29.4	65%	32.7
Power after incidence angle attenuation	*71%*	20.9	100%	32.7
Electricity generated	*27%*	**5.6**	27%	**8.8**

Note: 1) ADL simulation simulation resulting from the generated power after atmospheric attenuation but before applying coverage and filling ratio; 2) TAS simulation resulting from the generated power after atmospheric attenuation but before applying coverage and filling ratio

Key parameter	Electrolyzer unit CAPEX

▶ Used to compute **total ground PV + ELY station CAPEX** and stack replacement cost

Assessment	
Impact	High
Reliability	Medium

Values & Sources

380 €/kW	IEA[1]
1,440 €/kW	Air Liquide[2]

Low-end / High-end limit

320 €/kW	1,750 €/kW

RATIONAL

- The total amount of CAPEX required is determined based on the **electrolyzer (ELY) unit CAPEX** and the **installed capacity** on the GPS
- The new GPS are expected be deployed between 2035 and 2040, and will therefore benefit from a **decrease in CAPEX** *(table below)*
- The selected ELY unit CAPEX is the **average between 2030 low-end and 2050 high-end estimations**, resulting in **380 €/kW**

	Unit	2021	2030	2050
ELY unit CAPEX *(incl. turnkey factor)*	*USD/ KW*	1,000 – 1,750	400 - 440	320 - 340
			-70%	-21%

- The values above include the turnkey factor in addition to the electrolyzer system: electric equipment, gas treatment, plant balancing, and engineering, procurement and construction (EPC) ; in the case of electrolyzers using solar PV and offshore wind, the cost of the inverter is discounted
- Air Liquide estimates the **ELY unit CAPEX at 1,440 €/kW,** aligned with IEA data for 2021

Note : 1) "Global Hydrogen Review 2021: Assumptions annex", International Energy Agency ; 2) Consortium membe, world leader in gas and technologies

Key parameter	Stacks cost

▶ Used to compute **stack replacement cost**, included in the **total ground power station CAPEX**

Assessment	
Impact	Medium
Reliability	Low

Values & Sources

53 €/kW	IEA[1] + Air Liquide[2]
200 €/KW	Air Liquide[2]

Low-end / High-end limit

45 €/kW	245 €/kW

RATIONAL

- The stack of an electrolyzer must be replaced **every 7 years,** incurring a significant additional cost
- Its cost is based on the ELY CAPEX and is estimated approximately at (source: Air Liquide):
  - **22%** (excluding turnkey factor)
  - **14%** (including turnkey factor)
- The ELY unit CAPEX assumption selected is 380 €/kW (including turnkey factor)
- The stack cost is therefore 14%*380 = **53 €/kW**

Note : 1) "Global Hydrogen Review 2021: Assumptions annex", International Energy Agency ; 2) Consortium membe, world leader in gas and technologies

Key parameter	Solar Fuel Cell unit CAPEX

▶ Used to compute **total ground SFC station CAPEX**

Assessment	
Impact	High
Reliability	Low

Values & Sources

1,400 €/kW	Ademe, IEA

Low-end / High-end limit

700 €/kWh	2,100 €/kWh

RATIONAL

- SFC CAPEX are determined based on two factors **1) PV + ELY unit CAPEX** and **2) an estimated SFC / PV + ELY ratio**
  - The PV + ELY unit CAPEX is the sum of PV and ELY unit CAPEX *(table opposite)*
  - SFC is still a new technology, not well-developed on the market, therefore its construction cost is estimated to be **twice more expensive** than a PV + ELY station
- This assumption leads to an average cost / kg equal to 1.7 €/kg, compatible with the current stakeholders on this technology
  - Current cost is estimated today at 10 €/kg
  - Target cost is around 1€/kg (*year not precised*)

	Unit	Value
PV unit CAPEX	*€/kW*	**320**[1]
ELY unit CAPEX	*€/kW*	380
SFC / PV + ELY ratio	*x*	2.0
SFC unit CAPEX	*€/kW*	**1,400**

Note: 1) "Coûts des énergies renouvelables et de récupération en France", ADEME, 2019

Key parameter	SFC efficiency ratio

▶ Used to compute the **energy generated post SFC**

Assessment	
Impact	High
Reliability	Medium

Values & Sources

40%	Science Direct[1]
40%	ENGIE

Low-end / High-end limit

30%	50%

RATIONAL

- The yield rate of solar fuel technology can be measured in terms of energy conversion efficiency, which is the **percentage of solar energy that is successfully converted into chemical fuel**
- Solar fuel technologies are still in development and its efficiency is **today lower** than other technologies (10% for SFC vs 27% for PV)
- Yet, SFC appears **more promising** for H_2 production **without the intermediate production of electricity** and many actors are working on this technology to improve its efficiency
- The **efficiency of most investigated thermochemical** cycles is expected to range between **40–50%**

Note 1) "Screening of water-splitting thermochemical cycles potentially attractive for hydrogen production by concentrated solar energy", S. Abanades, 2006

Key parameter	WACC consolidated

▶ Used to compute the **consolidated discounted revenues, costs and energy**

Assessment	
Impact	High
Reliability	Medium

Values & Sources	
9%	TALDA
13%	TALDA

Low-end / High-end limit	
7%	13%

RATIONAL

- The weighted average cost of capital is a financial metric used to determine the **discount rate** for evaluating the present value of future cash flows and making investment decisions.
- It depends on the company's **capital structure** (split between **debt and equity**). Its formula is the following:

- $WACC = \frac{Equity\ market\ value}{Debt\ market\ value} * Cost\ of\ equity + \frac{Debt\ market\ value}{Equiy\ market\ value} * Cost\ of\ debt * (1 - \text{Tax rate})$

- A **WACC consolidated of 9%** was considered for this project based on several factors :
  - It is **a large-scale project** with a **high level of risk**
  - Yet, the risk is mitigated by **public investments,** and **lower risk profile investment** for ground power stations (WACC of 7%)

Parameter	Unit	Value	Impact	Reliability	Source	Comments
PV lifetime	years	30	Medium	High	Engie	
SFC lifetime	years	30	Medium	Low	Engie	
Energy needs for H_2 production	MWh/t H_2	60	Medium	High	Air Liquide	Include the energy of the H2 conversion and energy for managing water supply chain
H_2 energy content	MWh/t H_2	33	Medium	High	US department of Energy	• Energy content for lower heating value
Coverage ratio - Scenario Min / Max	%	65% / 90%	High	High	Engie	• % of retained power • Meteorological elements block incoming sunlight
Filling ratio - Scenario Min / Max	%	40% / 65%	High	High	Engie	• % of retained power • Equipement on the gorund prevent panels from being on all area • Moving panels need more free space and have a lower filling rate
Incidence Angle - Scenario Min / Max	%	100% / 71%	High	High	Engie	• % of retained power due to the angle between the panel and the DSR constellation in visibility • 71% is based on fixed panels with 45° of inclinasion

Parameter	Unit	Value	Impact	Reliability	Source	Comments
PV efficiency ratio	%	27%	High	High	Engie	
WACC PV & ELY	%	7%	High	High	IEA	
WACC SFC	%	9%	High	Medium	National Nuclear Laboratory	• Feasibility study conducted for small modular reactor
GPS construction spread N-1 / N-2	%	50% / 50%	Low	High	ADL	• If a GPS starts operations in N, 50% of CAPEX for its construction will be incurred in N-2 and 50% in N-1
PV unit CAPEX	€ / kWp	320	High	Medium	ADEME	• « Coûts énergies renouvelables et de récupération », 2019 • Estimation by 2050 = 320 – 550 €/kWp
Electrolysis vs solar PV capacity	x	1	Medium	High	ADL	• No oversizing assumed
Stacks replacement frequency	years	7	High	High	Air Liquide	
PV fixed O&M cost	€/kW	5.0	Medium	High	ADEME	

Parameter	Unit	Value	Impact	Reliability	Source	Comments
ELY fixed O&M cost	€/kW	2.3	Medium	High	IEA	
SFC fixed O&M cost	€/kW	10.9	Medium	Medium	ADL	• Assumed +50% compared to PV + ELY
Energy required for PV, ELY, SFC	kWh/kWp	2,000	Medium	Low	Sol Votaics	
Carbon emitted for PV, ELY, SFC	tCO2e/MWp	528	Low	Low	French ministry of ecological transition	
Carbon emitted per kWh electricity in EU	kg CO2/kWh	0.429	High	Medium	RTE	

LIFE CYCLE ASSESSMENT

Raw material | Carbon fiber and bio-fiber composites

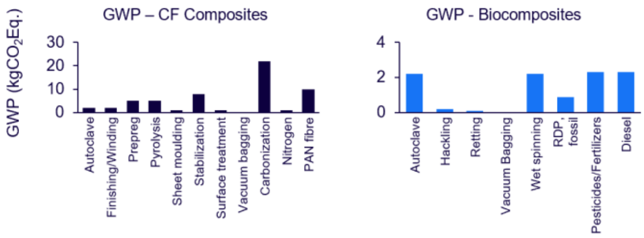
Scope

- **Functional unit** - Production of 1 kg of carbon fiber composites prepared from PAN (Polyvinyl cyanide) fibers and biocomposites of flax fibers from the farms prepared via vacuum bagging technique
- **System boundaries** – PAN / Flax Fibre production, composite preparation and waste recovery
- **Location** – UK as its one of the major producers of flax fibers with some industries which manufacture PAN and carbon fibers composites

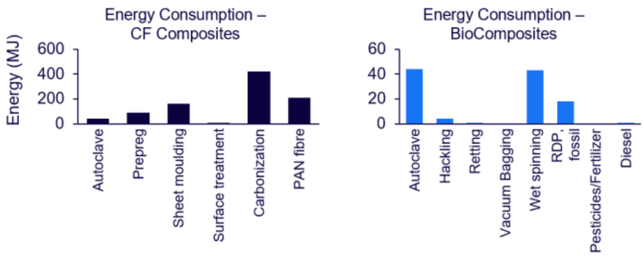
Life Cycle Impact Assessment findings

- Biocomposites production consumes about 202 MJ/kg whereas carbon fiber **composites required over 5x more** (1100 MJ/kg) due to a complex processes as carbonization
- Carbon fiber composites also resulted in ~**54 kgCO2eq.** total GWP which was about ~**4.5x more than biocomposites** (12 kgCO2Eq.) and other emissions were likewise higher than biocomposites except in certain scenarios

GWP of vacuum bagged preparation of carbon fiber composites & biocomposites



Energy consumption analysis of carbon fiber composites and biocomposites



Note: Abbreviations used: Carbon Fiber (CF), Global Warming Potential (GWP)

Raw material | Copper

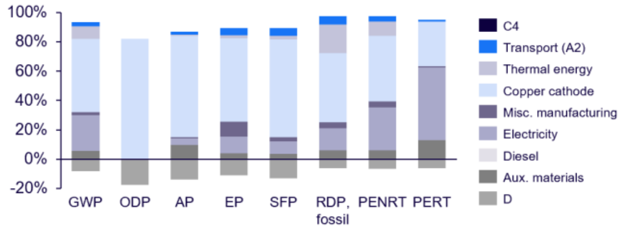
Scope

- **Functional unit** – Production of 1kg of copper sheets and copper tubes
- **System boundaries** – Raw material supply, Transport to manufacturer, manufacturing, disposal, recycling potential
- **Location** – North America

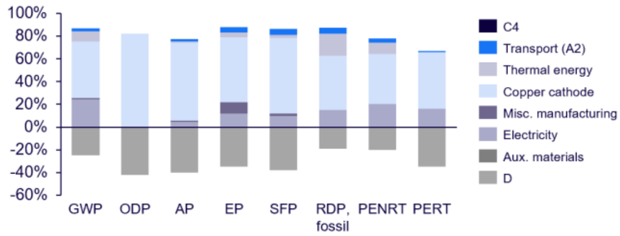
Life Cycle Impact Assessment findings

- The primary drivers are the **input of copper cathode, electricity, and thermal energy**
- Due to the copper cathode input, the **amount of recycled content is a key determiner** of overall impacts
- Additionally, the collection rate for recycling at end of life affects the amount of credit, or potentially burden, associated with module of D (recycling potential)

Drivers of impact
Copper sheet detailed results



Drivers of impact
Copper tube detailed results



Note: Abbreviations used are Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Euthrophication Potential (EP), Smog Formation Potential (SFP),Primary Energy Non-Renewable – Total (PENRT), Primary Energy Renewable - Total (PERT), Disposal (C4), Recycling potential (D)

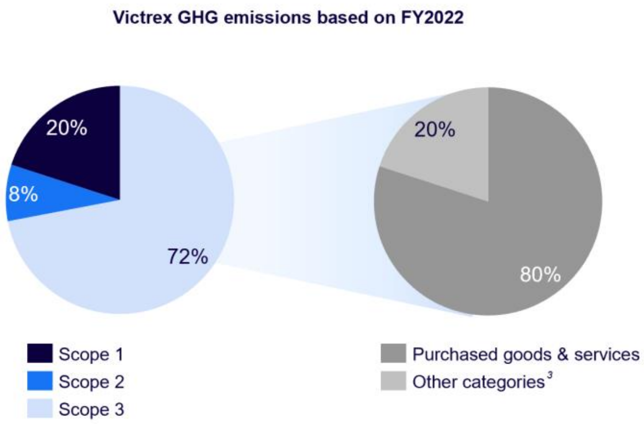
Raw material | **PEEK**

Scope

- **Functional unit –** Production of 1kg of PEEK by Victrex
- **System boundaries –** Scope 1[1], Scope 2[2] and Scope 3[3] based on GHG Protocol Corporate Standard
- **Location** - includes emissions from Victrex assets in the UK and overseas for FY2022

Life Cycle Impact Assessment findings

- **Scope 1 & 2 analysis** respectively resulted in **25ktCO2e and 11ktCO2,** leading to an **intensity measure** of **8kg CO2 per kg of PEEK manufactured**
- **Scope 3 analysis** resulted in **91ktCO2e** emitted and gives a total carbon footprint figure for **Scope 1, 2 & 3 of 127ktCO2e** (2022)
- All scopes considered, it equates to **28kg CO2 per kg of PEEK manufactured**



Note: 1) Scope 1 includes direct emissions resulting from combustion of fuels; 2) Scope 2 includes indirect emissions resulting from electricity and steam purchased (location-based method); 3) Scope 3 includes other indirect emissions across eight categories: purchased goods & services, capital goods, fuel and energy-related activities (not included in Scope 1 & 2), upstream transportation and distribution, waste generated in operations, business travel, employee commuting, investments